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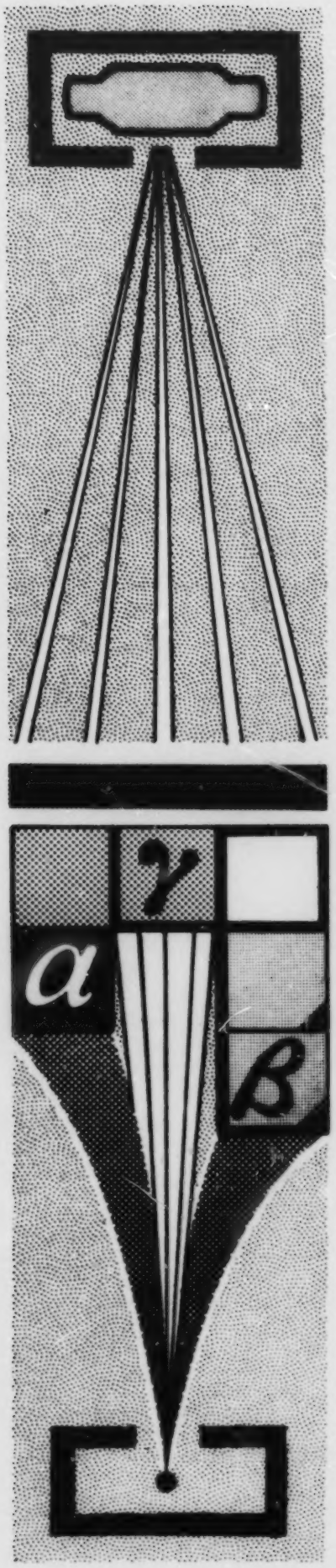

DESIGN and EVALUATION of an ELECTRONIC RADIOGRAPHY SYSTEM

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This report describes the development and evaluation of a low-exposure electronic radiography system with these major features: (1) reduction in x-ray photon requirements by a factor of approximately 100 in comparison with the usual high speed film-screen combination; (2) instant x-ray imaging and storage for immediate diagnosis, using an exposure time of approximately 1/60 second; and (3) adaptability to the usual televised x-ray image intensifier system.

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DESIGN and EVALUATION of an ELECTRONIC RADIOGRAPHY SYSTEM

Prepared by

William B. Miller, Jr., B.S.
Virgil D. Baker, III, M.S.
Heinz S. Weens, M.D.
James H. Larose, M.D.
Richard S. Colvin, M.D.
Alvin R. Moses, M.S.

Department of Radiology
Emory University School of Medicine

Under
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Public Health Service
FOOD AND DRUG ADMINISTRATION
Bureau of Radiological Health
Rockville, Maryland 20852

FOREWORD

The Bureau of Radiological Health implements a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Medical Radiation Exposure deals with 1) the reduction of unproductive ionizing radiation exposure of patients, workers and others exposed by the use of x rays and other machine-produced ionizing radiation, radioactive materials and radiopharmaceuticals, and 2) the improvement of radiological "systems" and methodology in the healing arts. A number of projects and studies are aimed at assessing and minimizing radiation exposure in the healing arts and increasing efficiency in the use of radiation in clinical practice.

Results of intramural and contractor projects of general interest are published as technical reports by the Division of Medical Radiation Exposure and distributed to State and local radiological health program personnel, Bureau technical staff and advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press and other interested individuals.

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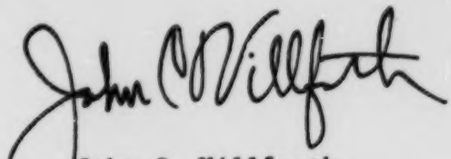

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

In order to achieve a significant reduction in unproductive medical x-ray exposure to the population, new concepts of diagnostic x-ray visualization and utilization must be generated, developed, and clinically evaluated. Recent developments in single frame television x-ray image storage provide a basis for "electronic radiography" systems which can achieve a marked reduction in radiation exposure to both patient and personnel.

Thus, the Division of Medical Radiation Exposure arranged a contract with the Department of Radiology of the Emory University School of Medicine. The Department designed a television x-ray image storage system to produce and retain images using fluoroscopic factors and extremely short exposures, and performed laboratory tests and clinical trials of the system.

This report describes the project. The resulting system combines the image integration capability of the television camera tube with a synchronized electronic memory to produce a continuously displayed television image from a conventional fluoroscopic image intensifier, using a single low-intensity x-ray exposure of 1/60 - 1/10 second. These images may be presented individually or at a predetermined sequence rate.

The electronic radiography system may be used for both fluoroscopic and radiographic techniques. In many situations it may be possible to replace continuous fluoroscopy with single or sequence instantaneous electronic radiographs, with 1/100 - 1/500 the usual fluoroscopic radiation exposure. In certain radiographic procedures acceptable images may be obtained with one to two milliroentgens per exposure, about 1/500 that required for a film radiograph.

The potential of electronic radiography systems can be realized only if accepted by users of diagnostic x-ray equipment. Consequently, the Emory University Department of Radiology is at this time conducting further clinical trials of the system in selected procedures.

Arve H. Dahl
Acting Director
Division of Medical Radiation Exposure
Bureau of Radiological Health

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DESIGN AND EVALUATION OF AN ELECTRONIC RADIOGRAPHY SYSTEM

1. BACKGROUND AND OBJECTIVES

During the past two decades, population exposure to ionizing radiation has been of major concern. The potential for genetic hazards, carcinogenesis, induction of leukemia, and shortening of lifespan has been widely reported and discussed (*1-10*). Appraisals of the contribution and importance of x-ray exposure from diagnostic roentgenology have been presented by numerous investigators (*11-26*). The Public Health Service X-ray Exposure Study conducted in 1964 by the Bureau of Radiological Health and the National Center for Health Statistics has been of particular importance in providing estimates of national population exposure and dose (*24,26*). Various reports indicate that medical x-rays may contribute significantly to the radiation exposure of the population, and to the genetically significant dose (*14,18,19,26,27*).

The evidence is sufficient to warrant a concerted effort to reduce the medical x-ray contribution to population dose. There is a recognized need for safe and conservative use of ionizing radiation in medicine and various recommendations appear in the literature (*14,27-29*). However, the reduction of medical exposure is complicated by the basic problem of obtaining sufficient radiologic information for a reliable diagnosis from a minimal patient exposure (*32,34*) as well as by the increasing use of x-rays in medical diagnosis (*24,27*). Along with more productive and efficient use of medical x-rays, there appears to be a need for new concepts of diagnostic x-ray visualization and utilization.

Since World War II there has been an increasing desire to improve diagnostic x-ray quality and reduce patient x-ray exposure (*27,28*). Developments in x-ray apparatus and accessories during the last twenty years have produced significant progress in both areas. For instance, the introduction of the x-ray image intensifier has increased the diagnostic value of fluoroscopic examinations and permits a reduction in exposure. One cannot be certain, however, that this development has resulted in a corresponding reduction in dose. The low exposure capability may easily be ignored, and exposure times may be prolonged as the information obtained becomes more meaningful. Such excessive exposure might be prevented by adequate training and experience. A further reduction in fluoroscopic exposure would then depend upon technical improvement of the imaging apparatus, or upon methodology which can considerably reduce the fluoroscopy time.

Many fluoroscopic examinations are so prolonged that considerable exposure may occur even with optimal fluoroscopic image intensification. The principal objective of fluoroscopic examination is the observation of moving structures. However, many of the prolonged procedures involve

very little motility and utilize fluoroscopy only as a convenient method of instantly obtaining x-ray images of a stationary object at different times. Foremost among such procedures are various types of vascular catheterization and orthopedic procedures such as hip nailing and fracture manipulation. It is estimated that evaluation of the fluoroscopic image may require several seconds (*46*); therefore, many times more x-ray photons are used than are essential for transmission of the information. The employment of serial radiographic films may also result in considerable exposure.

The information content of a radiologic image is determined by the distribution of x-ray photons transmitted by the patient during an interval of time. In order to minimize patient dose, these photons must be utilized as efficiently and completely as possible. If the desired individual images obtained by fluoroscopy could be instantly produced and retained using extremely short x-ray exposures, there would be a considerable reduction in patient exposure. If images obtained by this technique could also replace certain radiographic films, substantial dose reduction would again result; procedure time would also be reduced by eliminating film processing.

A review of various visualization techniques (*33,41-55*) led to an investigation of television image storage techniques and a research project to discover their capabilities for diagnostic x-ray visualization (see appendix A). The principal objective of the research was to show that a television x-ray image storage system could be devised to produce and retain images useful for certain examinations, using fluoroscopic factors and extremely short exposures to attain a considerable reduction in patient and personnel dose. The major research efforts were supported under a U.S. Public Health Service contract and encompassed the following activities:

1. Design and development of a "television system incorporating integrated image retention and display with conventional fluoroscopic image intensification."

2. Performance of a series of laboratory tests and clinical trials for technical and radiologic evaluation of the system with regard to reduction in x-ray exposure.

3. Investigation of the feasibility, advantages, and disadvantages of various analog and digital storage techniques or devices that might be applied for "the video memory element of the television image storage system developed under this contract."

The following sections of this report present important aspects of the system design, technical development and clinical evaluation resulting from these research activities.

2. SYSTEM DESIGN

2.1 INTRODUCTION

The television x-ray image storage system was proposed to meet the objective of exposure reduction by using the smallest possible x-ray exposure rate-time product to fulfill the minimum requirements of visualization. Modern fluoroscopic and television techniques were applied to obtain the best available x-ray detection sensitivity, a short image integration time, and an immediate image display. The resulting system design combines:

1. The high sensitivity of an x-ray image intensifier optically coupled to a television camera; with
2. Television camera tube image integration and retention; for
3. Single-frame television image recording and instant reply; using
4. A short duration x-ray exposure.

The system produces an x-ray image for continuous viewing on a television monitor, using an x-ray exposure of a fraction of a second with x-ray factors equivalent to those of fluoroscopy. This is quite different from recording a single television frame from conventional televised fluoroscopy as depicted in figure 1, because a short duration "radiography type" x-ray exposure produces the image, figure 2. Therefore, this television image storage technique is referred to as "electronic radiography."

The high sensitivity, low exposure capability of the image intensifier-television camera combination is evidenced by a review of x-ray visualization techniques, as presented in appendix A. The practical application of television techniques to radiology has been reported by numerous investigators (*36-48*). Of these, many applied methods for electronic storage of televised images from an x-ray image intensifier. Wallman and Wickbom used a direct-viewing television image storage tube for x-ray procedures in the operating room (*36*). Schut and Oosterkamp reported on "electronic photography" of the image using a magnetic wheel television recorder (*41*). Berci constructed a "stored telexray" device for fracture setting which used a storage tube with electrical readout (*42*). Bischoff and Schott described the use of a flexible magnetic disk recorder in x-ray diagnosis (*43*). Others have reported on video-tape recording of x-ray procedures (*39,40,46*). These techniques proved the usefulness of televised x-ray image recording and single-frame television image storage. But, because of one or more technical limitations, none offered the presently desired combination of low exposure and visualization capabilities.

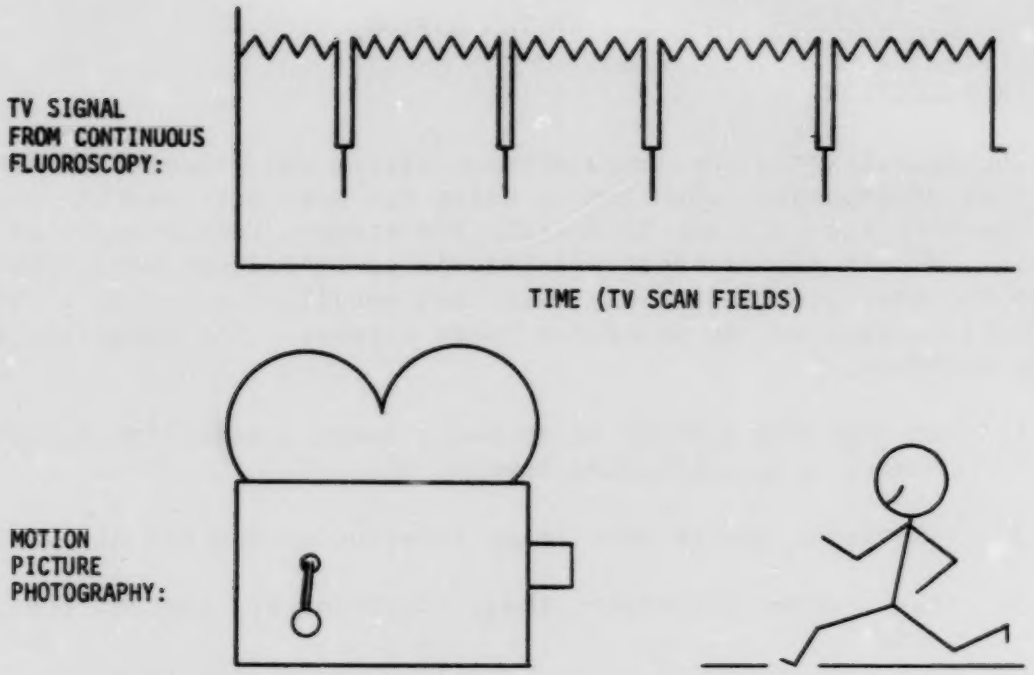

Figure 1. Continuous televised fluoroscopy is similar to motion picture photography: the photon flux is continuous.

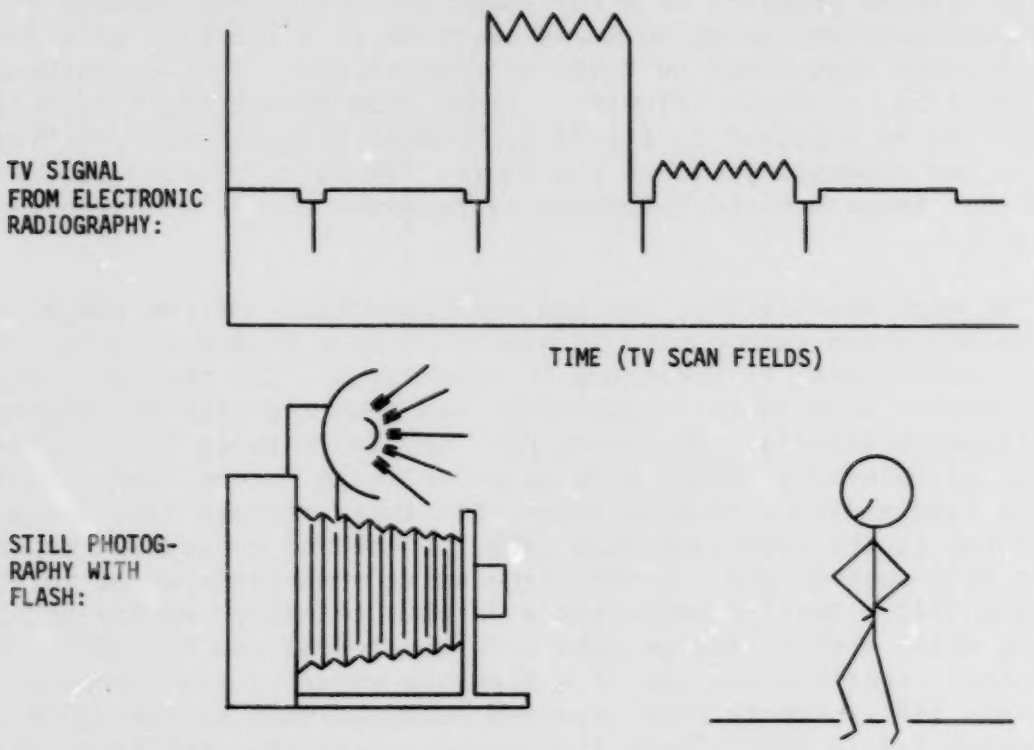

Figure 2. Electronic radiography is similar to still photography with flash: the photon flux is a single flash.

For instance, the video recording of a single frame from continuous televised fluoroscopy, figure 1, or repeated replay of a single frame from continuous video recording is inefficient and usually unsatisfactory. Many more x-ray photons are wasted than utilized in obtaining a single image because the photon flux is relatively continuous. And, when using the low exposure rates of televised fluoroscopy, the "still image" has a poor quality appearance due to the random spatial distribution of the few x-ray photons available during the recording time for a single frame (*46*). With the United States television standard of 30 frames per second of two interlaced scan fields, the effective recording time is fixed at 1/30 of a second for a single frame and 1/60 of a second for a single field. The randomness of the few photon-screen interactions occurring at low x-ray input prevents a complete image from being continuously present. Any "still image" acquired in 1/30 of a second appears granular because too few photons are accumulated during this time. Conventional televised fluoroscopy, or video-tape replay, appears satisfactory because the perceived image information is accumulated during the retinal action time of 0.1-0.2 second (*31*). The eye integrates the random fluctuations into a complete image.

The restriction on television camera exposure time and integration imposed by continuous television scanning does not permit selection of the least x-ray exposure rate-time product necessary to obtain an adequate single "still image." This limitation was overcome by taking advantage of the image retention characteristics of the television camera tube target and by using single-scan read-out.

Within certain limits the useful video output signal from a television camera tube is dependent on the flux-time integral of light impinging on the photosensitive target (*54,55*). This characteristic permits use of a wide latitude of camera exposure times to obtain a desired integration sensitivity. Depending on the particular camera tube used, the maximum integration time and sensitivity are limited by the accumulation of dark signal noise. There appears to be no limitation on use of very short camera exposure times and high quantum input rates. Schut and Oosterkamp alluded to the application of camera tube image retention by stating (*41*): "Television camera tubes themselves are also memory devices. One can expose them to light during a certain period and, after the termination of the exposure, feed the integrated electric picture, the so-called video signal, into the television system during one scanning period of usually 1/50 second. The time during which the image can be stored depends upon the type of camera tube used. In this way one would see on the screen of the television monitor one flash during the same 1/50 second." This aptly describes the basis of electronic radiography.

Camera tube scanning is inactivated during the exposure time interval, permitting the photosensitive target to integrate a complete image from a single exposure. Immediately after exposure, scanning is reactivated for

single-scan readout of the retained integrated image. The resulting "flash" of the single-frame image, figure 2, is stored by a magnetic disk recorder. The recorder provides immediate viewing and repeated playback of the single frame on a television monitor at conventional frame rate without deterioration.

Image retention and single-scan readout offer several advantages over continuous scanning. Any electrical instability in the scanning circuits will cause image distortion rather than image noise. And, since the television frame rate and exposure duration are not related to each other, continuous photon flux is not required. An x-ray exposure time and flux may be selected to provide the least number of x-ray photons needed for an adequate image.

Wallman and Wickbom accomplished an exposure reduction using a single-scan technique for image readout into a direct view television image storage tube (*36*). However, the system appeared to offer little of the desired operational flexibility and visualization quality because of limitations imposed by the image storage tube. The advantages and disadvantages of television image storage tubes are discussed in section 3 of this report.

Recording a television image requires rapid acquisition of a large quantity of information. A storage capacity of approximately one million bits of information is necessary to represent a single television frame of two interlaced fields with a resolution of 500 TV lines and several shades of gray. Each of the two fields must be recorded in 1/60 of a second. The best storage technique appears to be magnetic recording. High-fidelity single-frame recording and instant replay can be accomplished using a magnetic disk or drum rotating at a speed of one revolution per frame or 1,800 rpm. The first device of this type was developed by Philips Research Laboratories with promising results (*41*). Although never marketed, it led the way to improved versions marketed commercially by several manufacturers for "instant replay" of televised sports events. A recorder of this type was adapted for the electronic radiography system. This particular recorder provides for storage of 500 individual electronic radiographs on a magnetic disk. By mechanically shifting the recording head, 1-500 images may be stored indefinitely with no significant deterioration. This feature offers a convenient method of retaining electronic radiographs for photographing at a later time.

Television camera tubes, such as the orthicon, vidicon, SEC vidicon, and plumbicon (*47-55*), all have image integration capabilities adequate for single-scan readout and electronic radiography. The orthicon and SEC vidicon have relatively high sensitivity, fair resolution, and moderate dark signal noise, but are bulky, critical to adjust, and relatively expensive. The vidicon and plumbicon are less sensitive, but usually have less noise, fewer critical adjustments, and better resolution. The

basic difference between the vidicon and plumbicon is the composition of the photosensitive target. The target material of the vidicon is primarily antimony trisulphide, whereas that of the plumbicon is lead oxide. The plumbicon exhibits less image "stickiness" than the vidicon, but not as little as the orthicon; the plumbicon has less noise than the vidicon.

In the usual x-ray installation, either the vidicon or the plumbicon is used in preference to the much more expensive orthicon. Their sensitivity is sufficient to obtain adequate visualization with low x-ray input to the intensifier. Vidicon "stickiness" does not affect image integration. Image integration relies on the capacity of the photosensitive target to store electrical charge during exposure, whereas "stickiness" results from the relatively slow discharge of the target material during scanning.

Hence, the vidicon was chosen for the initial electronic radiography system evaluation. The characteristics of the particular tube used, as discussed in section 3, limited the maximum integration time to about 1/10 of a second. This is sufficient to provide the latitude in camera exposure time necessary in selection of the best x-ray flux-time relationship for the desired single frame image.

2.2 THE ELECTRONIC RADIOGRAPHY SYSTEM

A block diagram of the electronic radiography system is shown in figure 3. It consists of a conventional X-ray Generator and X-ray Tube, fluoroscopic Image Intensifier, and television camera chain (TV Camera and TV Camera Control) modified to permit external blanking of the camera tube scanning beam; plus the Video Memory (Magnetic Disk Recorder), TV Monitor for display of the "electronic radiograph," and a specially-designed Timing and Control Unit (with Footswitch) for synchronizing operation of the X-ray Generator, TV Camera scanning beam, and Video Memory.

Timing and synchronization of the various operations, as shown in figure 4, are of primary importance. All functions are synchronized with the television scanning period of 1/60 second generated by the TV Camera Control. This insures that electrical switching, in addition to being properly timed, will occur during a TV vertical retrace interval to prevent the appearance of switching noise in the image. Closure of the Footswitch initiates automatic operation of the Timing and Control Unit, switching "off" (blanking) the scanning beam and switching "on" the X-ray Generator, for a predetermined length of time. When the x-ray exposure terminates, the scanning beam is turned "on" (unblanked), and the magnetic disk records the single-scan TV signal containing the integrated image information. The recorder automatically replays the single-frame image

repeatedly for viewing on the TV Monitor. The total time required for image acquisition is 1/60 to 1/10 second for x-ray exposure and image integration plus the time for one complete TV scan. Only a fraction of a second elapses from the time the Footswitch is depressed until the image appears on the TV Monitor.

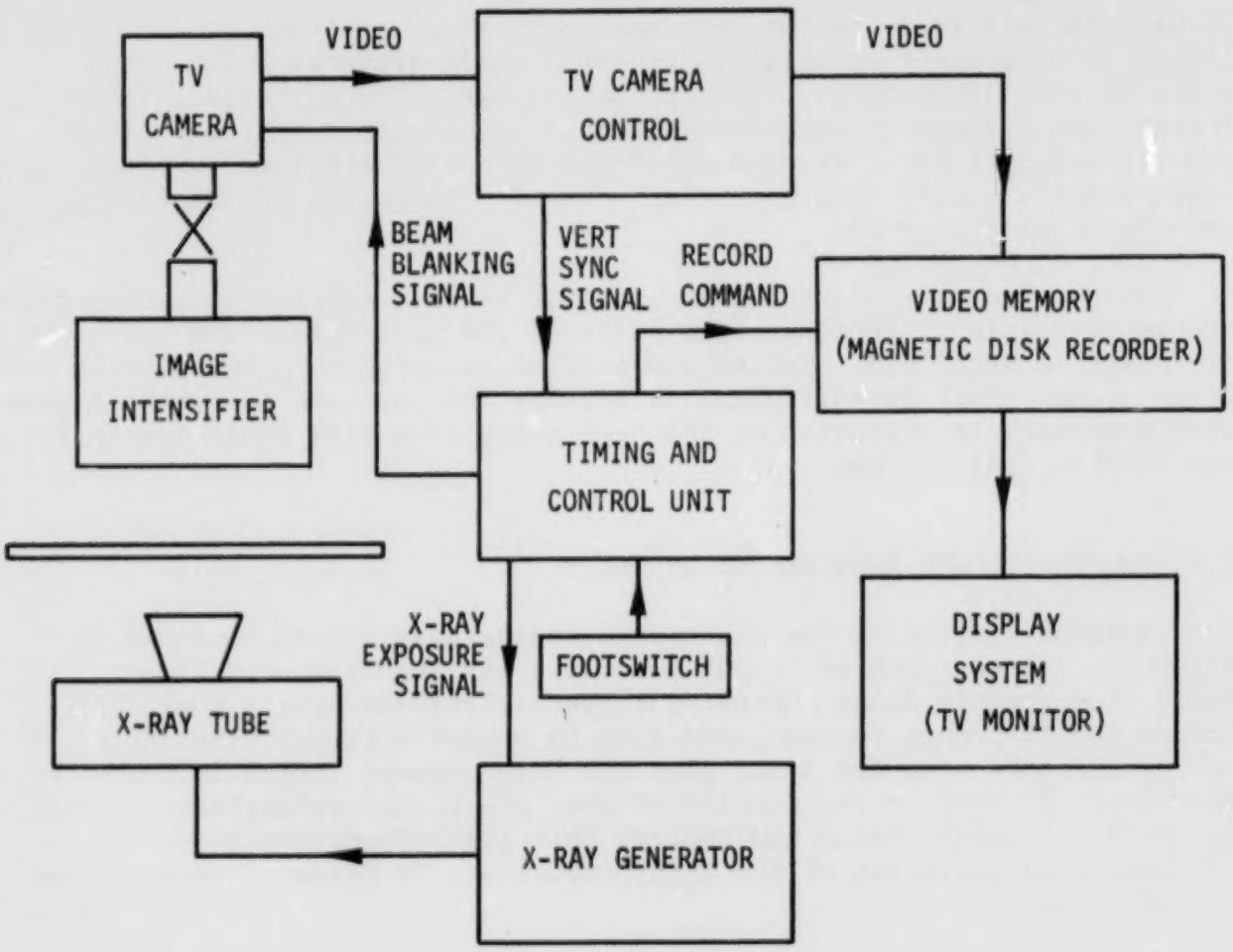

Figure 3. Simplified block diagram of electronic radiography system.

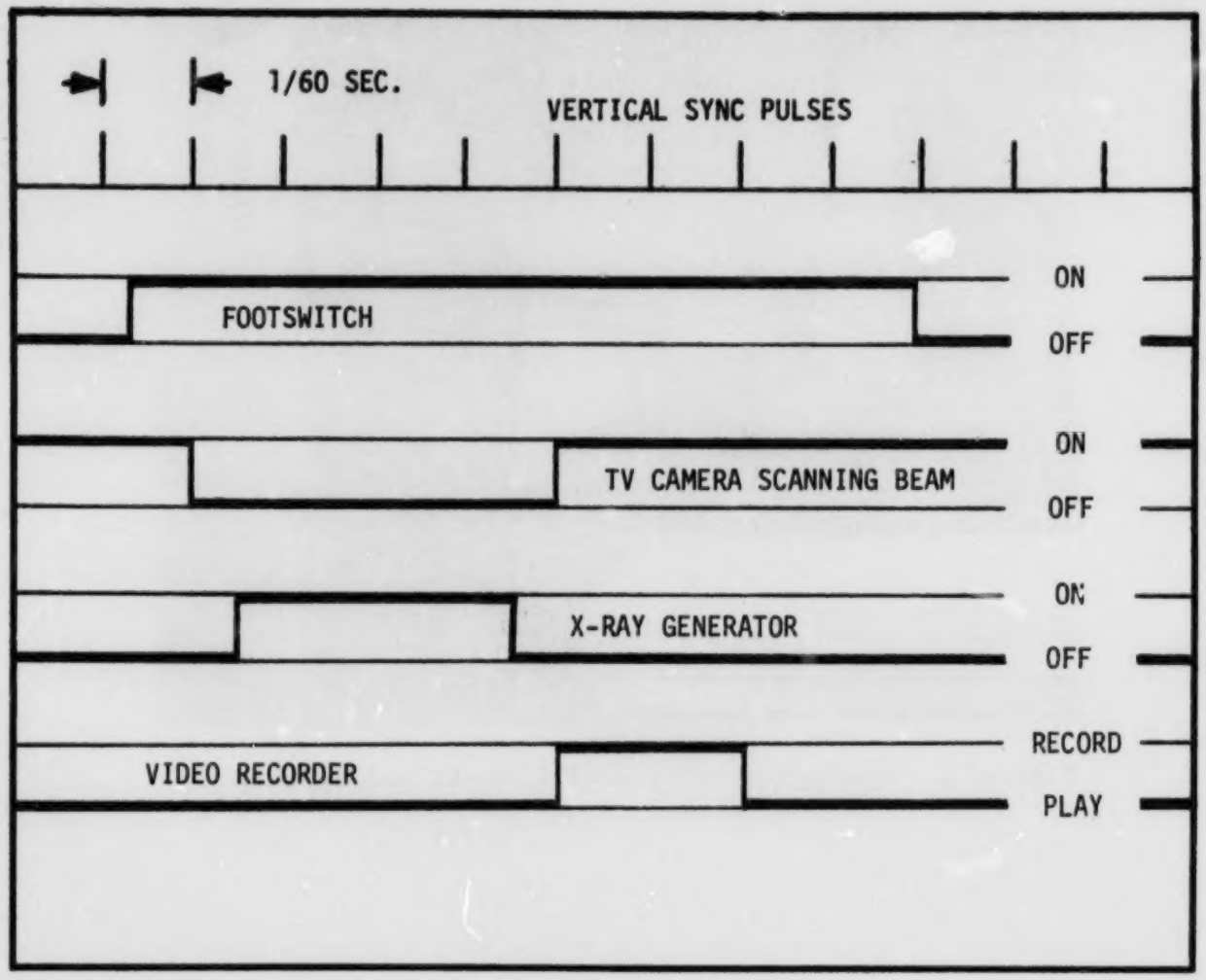

Figure 4. Operational timing for electronic radiography.

A photograph of the electronic radiography equipment installation is shown in figure 5. Operation of the system is extremely simple. Through the use of two footswitches, the fluoroscopist may select: (1) Conventional real-time fluoroscopy with televised image intensification, (2) electronic radiography producing a single image on momentary footswitch closure, or (3) electronic radiography producing sequential images at a pre-selected rate with continued switch closure. In the second mode, the last image remains on display until the footswitch is again depressed. Technical details of system operation are presented in appendix B.

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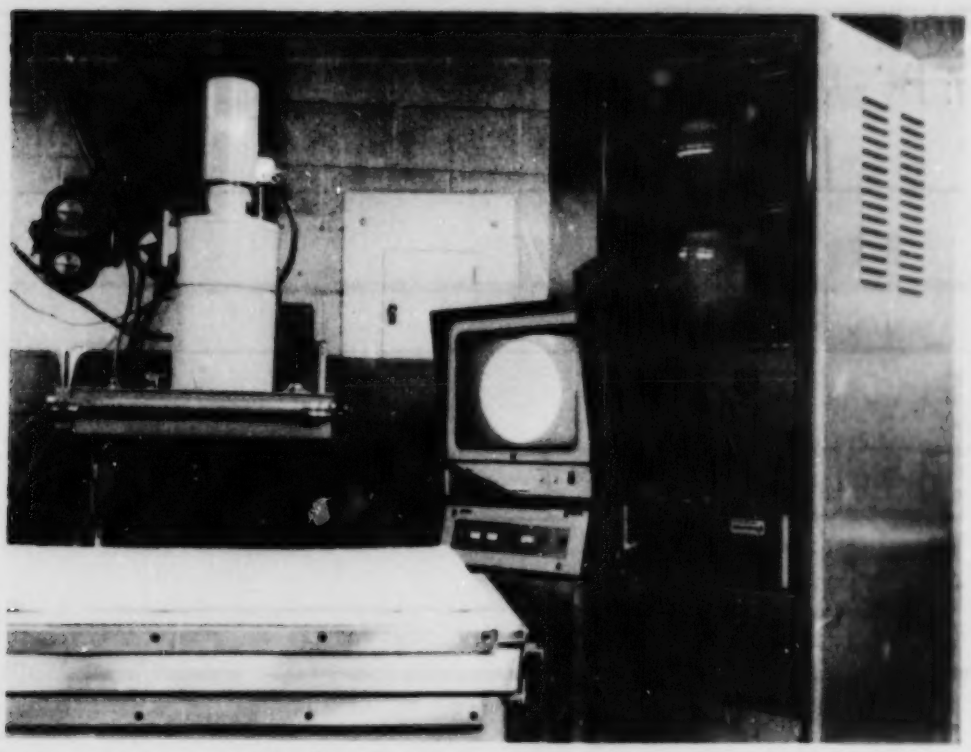

Figure 5. Photograph of the electronic radiography installation.

A simplified system for electronic radiography was devised which uses a Polaroid camera to record the single-scan readout and eliminates the video recorder, as shown in figure 6. All other components are identical in the two systems. With the Polaroid Camera focused on the TV Monitor screen, the exposure sequence is initiated by the photoflash synchronization contacts of the camera shutter. The duration of the x-ray exposure is determined either by the Timing and Control Unit, or, preferably, by a phototimer coupled to the output of the Image Intensifier. The camera shutter speed is 1/5 to 1/2 second on the Polaroid Model 180, or the "Normal Setting" on other models. The resulting 1/60 second "flash" of the integrated image is photographed when it appears on the monitor. The exposure sequence is only a fraction of a second, the same as with the all-electronic system, and the Polaroid print is available in about 10-15 seconds. In order to maintain proper black level for photography, the TV Monitor must have direct current restoration in the picture tube circuit.

The Westinghouse X-ray Division has also developed a television image storage system using a magnetic disk recorder (*70*). It is similar to the system reported herein and may be used for "electronic radiography" with resulting exposure reduction. Westinghouse has furnished a system for testing and evaluation in the Emory University Department of Radiology. The results of tests conducted with their magnetic disk recorder are included in section 3. Other testing and clinical evaluations of the Westinghouse system are presently underway. The Westinghouse system is also being evaluated by others for comparative exposure reduction, and contrast enhancement by use of its image subtraction capability (*71*).

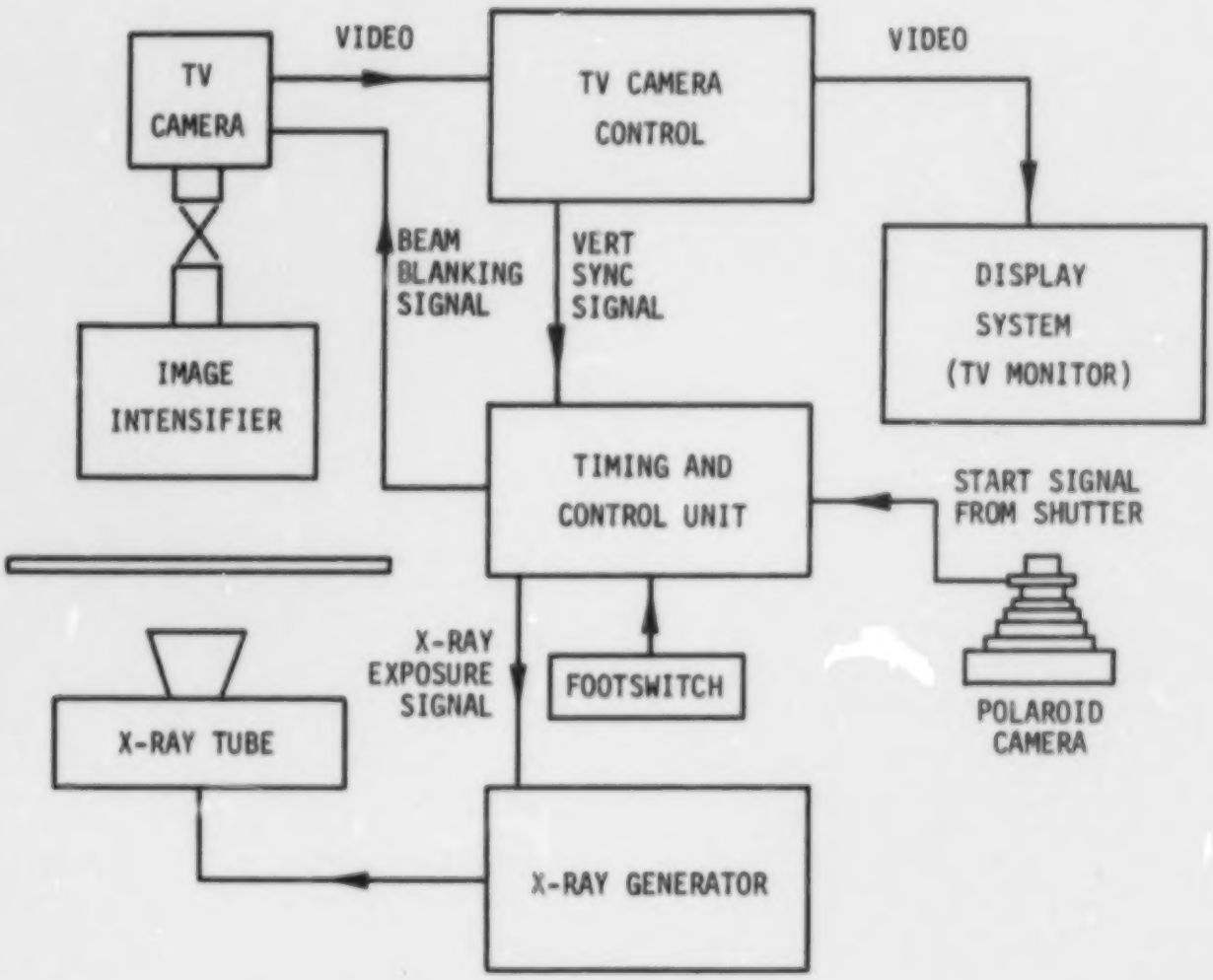

Figure 6. Block diagram of simplified electronic radiography system.

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3. TECHNICAL DEVELOPMENT

3.1 IMAGE INTEGRATION AND SINGLE-SCAN READOUT

In the vidicon camera tube the target material is formed into a thin photoconductive layer. When not illuminated, the layer behaves like an electrical insulator; when illuminated, it behaves like a conductor. The degree of conductivity is a function of the light intensity. An electron beam focused on the rear surface of the target scans the picture area, depositing an electric charge (figure 7). The front surface is maintained positive with respect to the charge deposited on the rear. When an area on the photoconductor is illuminated, the resulting conductivity allows the negative charge on the rear surface to neutralize the charge on the front. The degree of discharge at any given point on the target is established by the intensity and duration of the illumination at that point. The ability of the photosensitive material to store electrical charge permits accumulation of a discharge pattern representing the optical image focused on the target. Interruption of electron beam scanning during illumination results in target integration of the image information for the duration of exposure. Immediately after exposure, charge deposition by resumed scanning produces an electrical output signal representing the integrated image. This process neutralizes the stored discharge pattern and destroys the image.

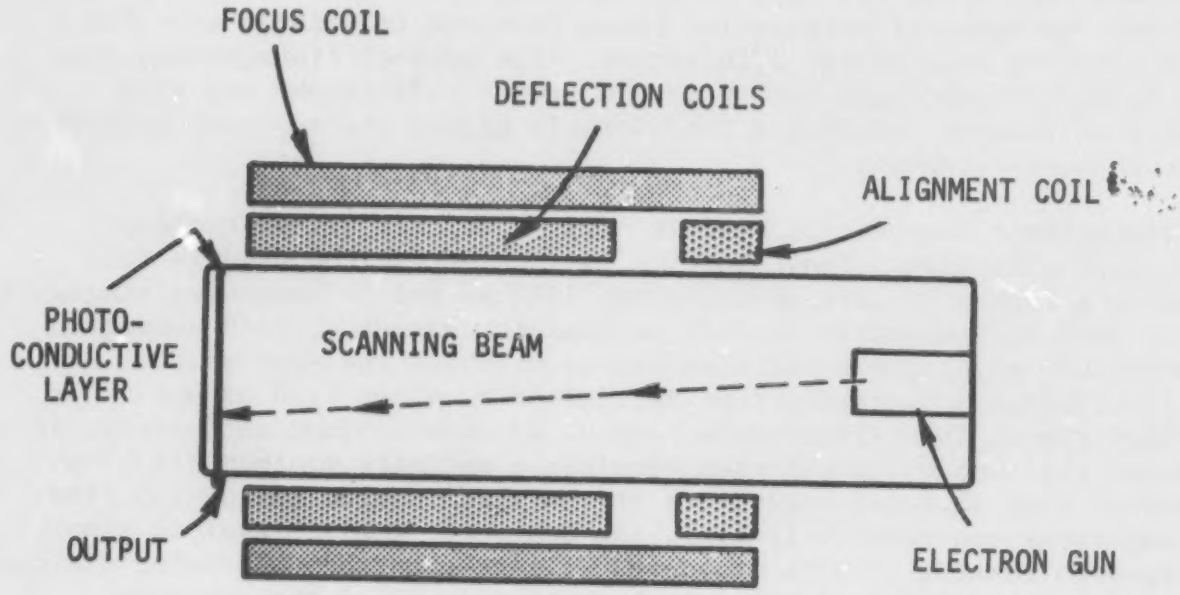

Figure 7. Structural arrangement of a typical vidicon camera tube.

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In practice, the photoconductor is not a perfect insulator when darkened, and exhibits varying degrees of conduction when illuminated. Thus, even when not illuminated, the charge deposited by the electron beam will remain for only a short period of time. The electrical charge on the rear surface gradually passes through the photoconductive layer to neutralize the charge on the front surface. Thus, when scanning an unilluminated target, a small charge must be replaced. The resulting signal output is called the dark signal, dark current, or noise. In normal operation with continuous scanning the dark signal is usually insignificant. When integrating an image, however, the dark signal is also integrated and can create an overall image fog. The degree of image fog or dark signal is dependent on the characteristics of the photoconductor and the integration time.

As previously noted, the scanning process destroys the integrated image. Approximately 90 percent of the image information is contained in the video signal from the first scan after exposure. The amplitude of this useful video signal increases with increase in integration time until image high-light saturation on the target. The residual signal from the second scan also increases uniformly, but is never more than about 10 percent of the useful signal.

The changes in video signal and dark signal levels as a function of different beam-off integration times are shown in figure 8. With the vidicon continuously exposed to a suitable image source, the video signal output was determined for continuous scanning (zero beam-off/integration time) and for beam-off/integration times from one television scan field, 1/60 second, to six fields, 1/10 second. The beam-off/integration time is an extremely important factor in electronic radiography and with single-scan readout provides a considerably higher video signal amplitude than continuous scanning.

The maximum integration time is limited by dark signal buildup and/or highlight saturation. For the particular vidicon used in this system, the degree of dark signal after 1/10 second of beam-off/integration time is just sufficient to produce noticeable image fog; with normal illumination, highlight saturation occurs at about the same point. Therefore, image integration time is limited to about 1/10 second. For the video signal from single-scan readout to have maximum uniformity, it was found that the vidicon target requires a definite minimum blanking (beam-off) time interval regardless of the illumination (exposure) time. When exposures are relatively long, the beam-off time interval is simply the exposure interval. With exposures of less than one television field, however, the blanking interval must be extended beyond the exposure interval. If not, low signal amplitude and vertical shading occur. The extended blanking interval is necessary to provide time for complete formation (charge migration) of the electron image before readout. Determinations were performed with several camera tubes (vidicon and

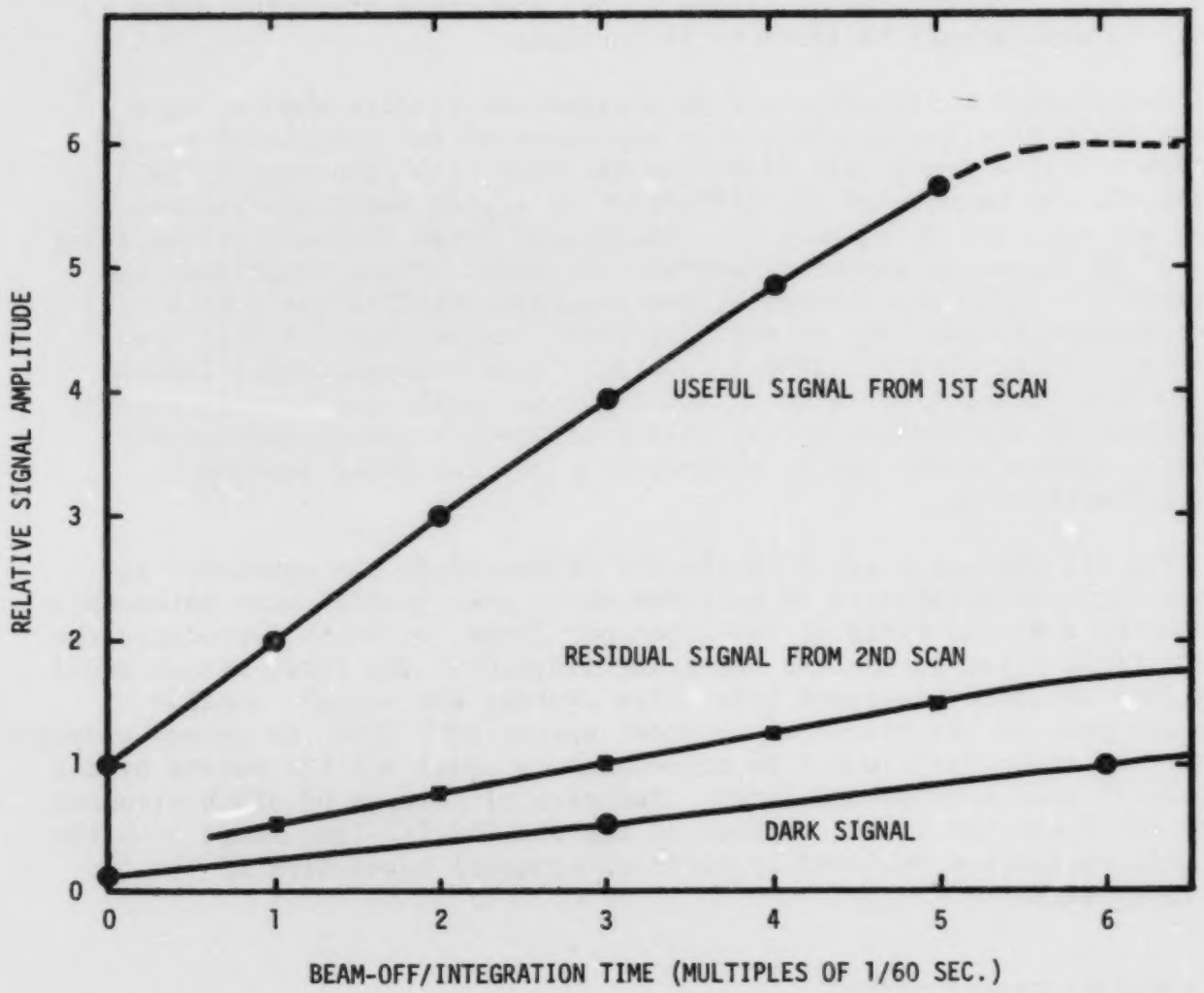

Figure 8. Vidicon integration time vs. video signal amplitude for useful signal, residual signal, and dark signal.

plumbicon) using optical illumination intervals down to 0.8 μ second. The optimum blanking time interval ranged from two to six television fields, depending on the particular tube.

The linearity of the television camera chain operated in the storage mode is also demonstrated by figure 8; and the ratio of useful video signal to dark signal is shown to be constant.

There are two disadvantages in single-scan readout when using a camera chain with the standard scan parameter of two interlaced fields to form a single frame (EIA RS-170 or RS-300): (1) The second field is not visible because of the difference in signal amplitude between the first and second scan (figure 8). The viewed image flickers at the frame-rate of 30 times per second. Careful adjustment of the brightness and contrast on the monitor, however, can suppress the "flicker effect" to an acceptable level. (2) Of more importance is the loss of half the horizontal lines (262 1/2 lines) in single-scan readout, which limits the vertical resolution to about 200 TV lines (lines per picture height) regardless of the resolution capability of the electronic radiography system. System resolution is discussed in the following section on imaging capabilities.

The flicker and loss of resolution evidenced in the experimental system might be eliminated by a system which uses special scan parameters to provide a single field of 525 lines per frame, or which reproduces the single field twice during the one-frame playback. The first method would require a specially-designed television system; the second, another playback head on the videodisk recorder spaced 180° from the record-playback head. The first field would be reproduced as usual and the second by the additional head 1/60 second later. The resulting image of 525 horizontal lines would consist of two replays of the one 262 1/2-line image with the vertical resolution improved by vertical aperture correction of the output video signal.

3.2 IMAGING CAPABILITIES

The imaging ability of the television camera chain selected for the electronic radiography system was judged by its modulation transfer ratio (*58,59*). This was determined from the amplitude envelope of the television signal generated by camera observation of a test object with square wave density modulation and a variable spatial frequency. In this case, use of square wave rather than sine wave intensity modulation is justified because the TV system passes only the fundamental frequency at high spatial frequencies. As frequency increases, amplitude response decreases, and the modulation becomes essentially a sine rather than

square wave. The response as shown in figure 9 is desirable; it yields a high contrast image with good apparent sharpness. AT 20 percent of the maximum response, the resolving power of the camera chain is approximately 440 lines per picture width, or scan width.

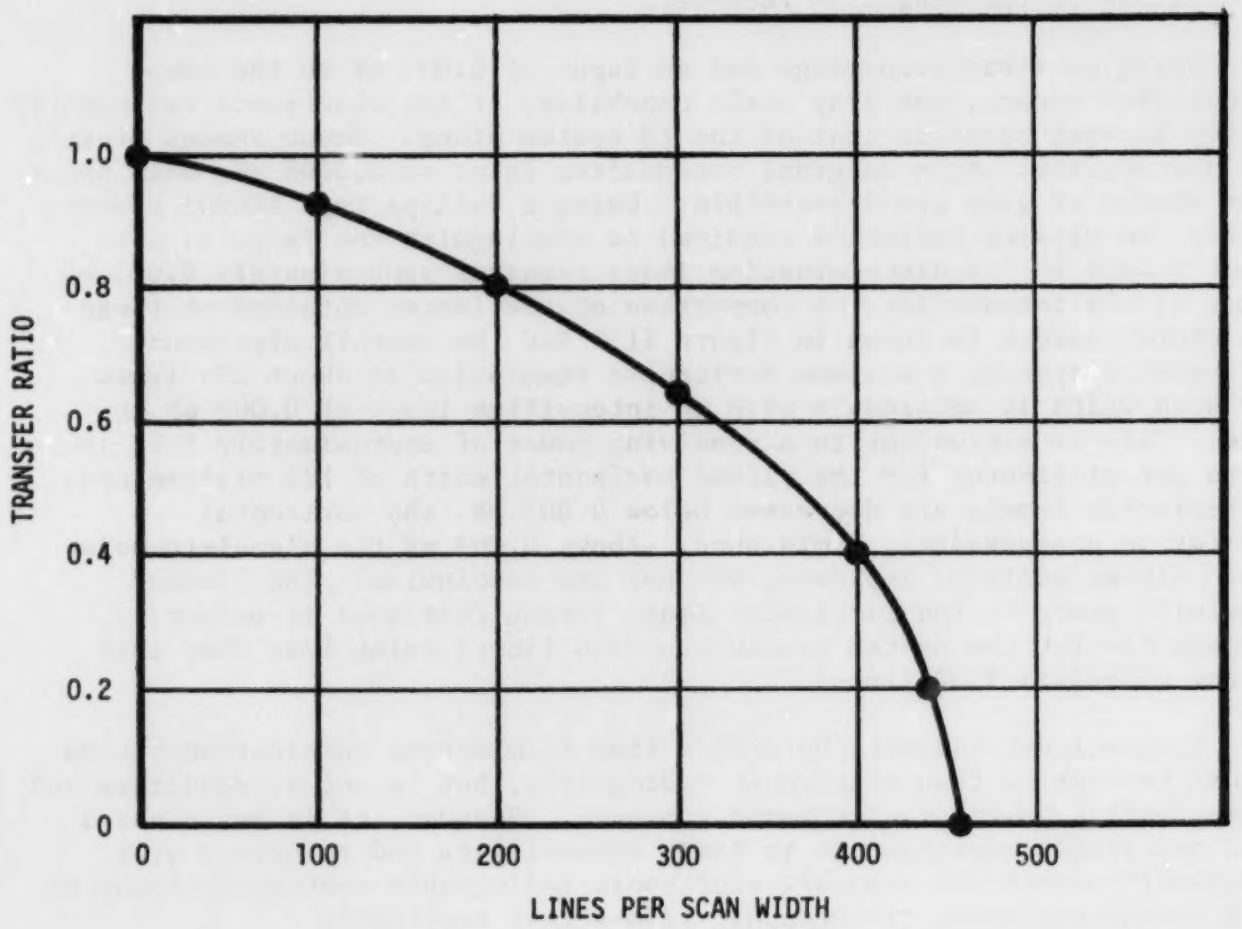

Figure 9. Modulation transfer ratio vs. resolving power for the television camera chain selected for the electronic radiography system.

In a similar manner, the limiting resolution of the vidicon camera tube alone was determined experimentally. The frequency limitation of the video amplifiers was overcome by reducing the horizontal scan rate from 15,750 to 60 scans per second. At 20 percent of the low frequency response the resolution of the vidicon alone is approximately 900 lines per scan width.

The spatial resolution and gray scale of the camera chain with videodisk recorder were judged by viewing a standard converging line pattern and gray scale test chart on a high resolution monitor. The resolution and gray scale reproduction for a stored image is similar to that of the real-time image, as shown in figure 10. The gray scale is essentially the same, about seven shades, but the horizontal resolution of the stored image is restricted to approximately 330 lines by bandwidth limitations of the videodisk recorder.

Using an x-ray step-wedge and an input of 0.003 mR to the image intensifier screen, the gray scale capability of the electronic radiography system is equivalent to that of the TV system alone. Seven shades of gray are discernible. At a marginal intensifier input of 0.0006 mR, only about four shades of gray are discernible. Using a Philips Type XG6001 Phantom Plate, the minimum radiation required to distinguish the image is also about 0.0006 mR. A discriminating image requires approximately 0.003 mR input to the intensifier. A comparison of the images obtained at these two photon levels is shown in figure 11. For the overall electronic radiography system, a maximum horizontal resolution of about 300 lines per scan width is obtainable with an intensifier input of 0.003 mR or more. This is equivalent to a resolving power of approximately 1.2 line pairs per millimeter for the viewed horizontal width of 125 millimeters. As radiation levels are decreased below 0.003 mR, the horizontal resolution progressively diminishes. Above 0.003 mR the signal-to-noise ratio (image quality) improves, but not the resolution. The limited resolving power of the particular image intensifier used is primarily responsible for the system resolution (300 lines) being less than that of the videodisk (330 lines).

Conventional radiography with a fast film-screen combination yields higher resolution than electronic radiography, but is not as sensitive and consequently results in increased exposure. However, it is anticipated that continuing improvements in image intensifiers and recorders will eventually permit low exposure electronic radiography systems to equal or even exceed the usual radiographic film-screen resolution.

The resolution obtainable with high-speed film and high-speed screens is approximately five lines per millimeter. It is important to consider the x-ray beam quality and photon fluence required to deliver sufficient quanta for an image of this resolution. Also, a distinction must be made between the information carried by the beam and the information extracted by a detecting medium. The beam always contains more information than the resulting image. And, because of the nature of x-ray emission, the distribution of photons is not uniform in either time or space.

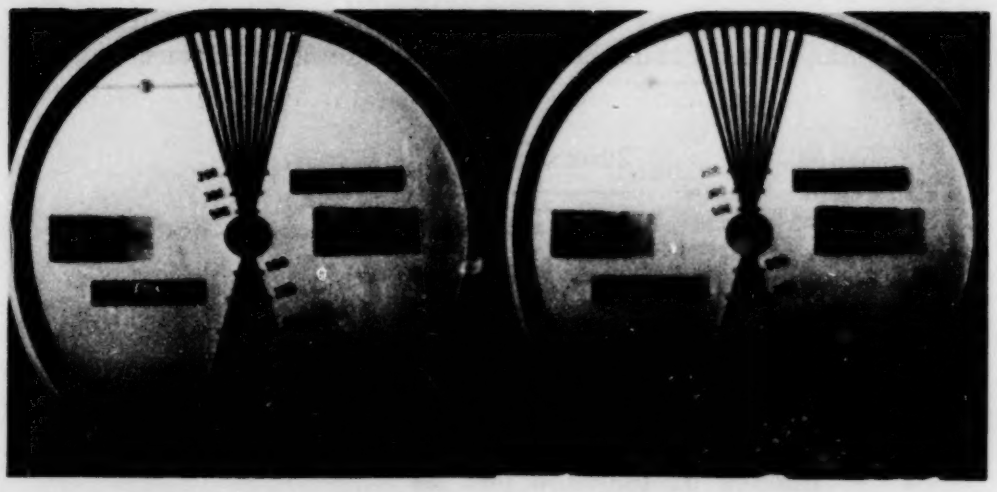

Figure 10. Comparison of a real-time television image (left) and an integrated image stored by videodisk recorder (right).

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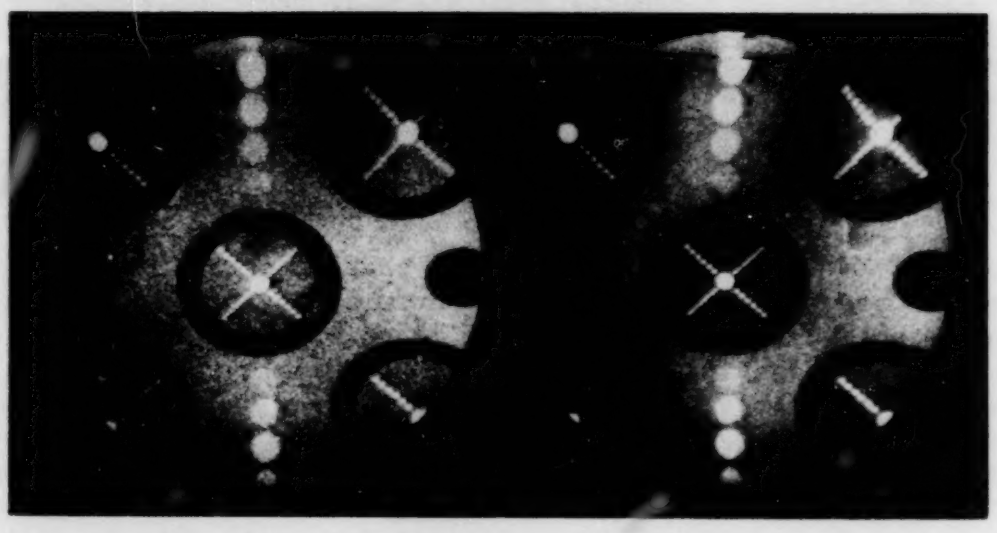

Figure 11. Comparison of electronic radiographs obtained with different exposure times. Left image obtained with 1/30-second x-ray exposure, for 0.0006 mR input to image intensifier screen; right image took 1/5 second, for 0.003 mR input.

The relationship between subject contrast, minimum perceptible diameter, and number of photons (taking into account the statistical fluctuations in photon distribution) has been shown by Strum and Morgan (*34*) to be:

$$\delta = \frac{200k\sqrt{g}}{C\sqrt{n\pi}}$$

where:

δ = minimum discernible diameter in mm

C = subject contrast in percent

k = threshold contrast to fluctuation ratio

n = number of photons per mm^2

g = amplification factor of the roentgenoscopic process

For example:

If the average energy of the photons reaching the film is assumed to be 50 KeV, and 1 mR is required to produce a density of one on the high-speed film-screen combination, then 2.8×10^5 photons per square millimeter are incident on the film-screen combination (*60*). For a subject contrast of 100 percent and using k = 5 (*31,38*) with this photon fluence at the image plane (g = 1) the theoretical minimum perceptible diameter is approximately 1/100 millimeter. Hence, a theoretical resolution of about 50 line pairs per millimeter would be possible with an ideal detector.

The usual film-screen combination is a poor detector by comparison. The film-screen resolution of five lines per millimeter could be obtained by an ideal detector with only about 0.01 mR of exposure at the image plane (*34*). X-ray image intensifiers are theoretically capable of greater resolution than film-screen combinations for a given photon input, because of their higher overall quantum efficiency (*29,32*). However, present image intensifiers are capable of a resolution of only about two lines per millimeter at 100 percent contrast. Assuming a quantum efficiency of 10 percent for an image intensifier and k = 5 for small objects (*38*), this minimum perceptible object size of 0.25 mm could be obtained with about 0.02 mR input to the screen.

3.3 THE ELECTRO-MECHANICAL VIDEO MEMORY

Although the selected video magnetic disk recorder was quite capable of storage and replay of the televised x-ray image information with excellent fidelity, two serious mechanical problems were encountered during initial tests. On one occasion the record-playback head was destroyed by mechanical contact with the rapidly moving disk; several other times, the disk surface was severely scratched by dirt particles on the head. Also, occasional failures of the system to synchronize disk rotation speed and television frame rate caused waviness and distortion in the stored image. Consequently, these problems were investigated and several additional magnetic disk recorders were also evaluated.

3.3.1 *Head-Disk Separation*

Video magnetic disk recorders require nearly intimate contact between the record-playback head and the highly-polished metal surface of the rotating disk. A loss in signal amplitude occurs during recording and playback, in proportion to the spacing between the head and disk surface, by the following relationship (*62*):

$$\text{loss (db)} = \frac{54\ D}{\lambda}$$

where D = head-disk separation

λ = wavelength recorded on the disk.

The loss in signal amplitude may be calculated for any recorded wavelength and finite head-disk spacing. In the recording process a frequency range of about one octave is involved; different frequencies are not equally attenuated. Furthermore, of the many factors which affect signal amplitude, only head-disk separation is considered here:

The recorded wavelength is dependent on the signal frequency and the linear speed of the disk with respect to the head. If the disk rotation is 1800 rpm (30 rps) and the track diameter is 11 inches, the linear speed is 1,036.2 inches per second. At the highest used video frequency of about 5 MHz (peak white) the minimum recorded wavelength will be:

$$\lambda_{min} = \frac{V}{f_{max}} = \frac{1036.2}{5 \times 10^6} = 207.2 \times 10^{-6} \text{ inches,}$$

or about 200 microinches. If this value is inserted in the previous equation, it is evident that the head-disk spacing must be extremely close in order to limit high frequency video component loss to acceptable levels.

Head-disk separation is maintained by an air-film generated and carried along by the spinning disk. Spring pressure on the head opposes the air-film and forces the head closer to the disk. Head-disk spacing is influenced by the surface area of the head, disk speed, and spring pressure. Spacing can be determined by comparing the output at normal speed with the output at low speed with the head contacting the disk. With no air-film, head-disk contact may easily scratch the disk surface; caution must be observed when operating a recorder at reduced speed. Signal amplitude varies with rotational speed and head-disk separation, according to the following relationship:

$$D = \frac{20\lambda}{54} \log_{10} \frac{(A_1 W_0)}{(A_0 W_1)}$$

where:

D = head-disk separation

λ = wavelength of recorded signal

A_0 = playback amplitude at normal speed

A_1 = playback amplitude at reduced speed

W_0 = normal rpm

W_1 = reduced rpm.

Using the above equation, measurements indicate the usual head-disk separation to be about 50 microinches.

With such close spacing, the head is likely to collect foreign matter from the disk surface. Air-film pressure is not sufficient to support a dirt particle of small area at the same height as the head. Consequently, the dirt particle may drag on the disk and cause the accumulation of more foreign material such as airborne vapors containing tar or other constituents of smoke. Eventually, the dirt buildup will abrade the surface of the disk. If the accumulation becomes sufficiently thick, the head-disk spacing will increase and impair picture quality. Ultimately the protective plating on the surface of the disk may wear through and permit the head to gouge the disk. When this occurs the head and disk are usually destroyed. When the head is fixed in one position,

the area swept by the head equals the width of the head times the circumference of the track. If the head is moved for multiple-frame recording, the swept area is much larger and the probability of dirt accumulation is increased.

Dirt buildup created problems with two of the recorders tested. One uses an aluminum disk plated with a nickel-cobalt magnetic recording surface, and a head with metallic magnetic poles. The disk surface is soft and easily scratched, so the head must never touch the disk. It is lifted from the disk during standby, and whenever the rotational speed is too low to maintain an air-film. The recorder housing is a loose-fitting plastic cover which allows dirt to enter. An attempt to seal the housing did not solve the problem. The most effective method of controlling dirt accumulation in this recorder is routine cleaning of the head and disk after every 10 hours of operation or once a week, whichever occurs first.

The second recorder has an aluminum disk plated with a nickel-cobalt recording surface plus a protective overplate of rhodium, and a head with magnetic poles of highly-polished ferrite. The poles are in contact with the disk at low rotational speeds and during standby. The rhodium overplate prevents the head from scratching the disk, but its finite thickness reduces the signal amplitude slightly. Extensive measures are used to prevent entry of foreign matter into the recorder housing. The disk chamber has a gasketed metal cover and a high velocity filtered-air circulation system. The likelihood of dirt accumulating is substantially reduced, but not completely eliminated. Initial adjustments required operation of the recorder with the cover removed. During this period the head and disk were cleaned several times, but apparently dirt accumulated in the housing. Several days after the disk chamber was closed, dirt buildup caused head-disk contact, destroying the head. After repair and cleaning another contaminate appeared; a brown gum-like material that could only be removed by an organic solvent such as xylene. This probably originated inside the housing from an organic vapor which condensed on the disk surface. A routine cleaning schedule prevented further trouble.

No head-disk contamination problems were experienced with the third recorder tested. This recorder, used by Westinghouse in their x-ray image storage system, also uses an aluminum disk with nickel-cobalt recording surface and protective rhodium overplate, and has heads with poles of highly polished ferrite which touch the disk during standby or slow rotation. The housing is sealed by a metal cover, but has no air circulation or filtration. The manufacturer recommends that the disk chamber never be opened except under clean-room conditions. The lack of a dirt accumulation problem with this recorder encourages speculation that other present-day video disk recorders could be re-designed to be maintenance-free.

3.3.2 *Synchronization*

In video disk recording, synchronization of frame rate and disk speed is extremely important. Disk speed must be stable and accurate. The instability problem encountered with the selected recorder led to an evaluation of two basic synchronization techniques. In one, a servo-mechanism adjusts rotational speed of the disk to coincide with the TV sync signals from the camera chain. In the other, camera scanning is controlled by prerecorded sync signals from the disk.

The servo-controlled recorder is easily integrated with television systems having crystal-stabilized synchronization. Disk rotation generates a tachometer signal for comparison with the sync signal. If the two do not coincide, the resulting error signal corrects the speed of the disk motor. With a disk speed of 1800 rpm, the disk must record exactly one complete TV frame in one revolution. A disk rotation less than 360° during the frame interval deletes a portion of the frame and causes severe tearing of the image on replay, while rotation exceeding 360° causes a similar distortion.

In a simple servo-control which uses only the vertical TV sync pulses, a comparison of sync with rotational speed occurs only once each 1/30 second, vertical pulse to vertical pulse. This is only once each revolution at 1800 rpm. Additional stabilization derived from the tachometer is necessary to maintain constant rotational speed between comparisons. In more sophisticated recorders the tachometer also produces a signal for comparison with the horizontal TV sync pulses. During the vertical interval the rotational speed is corrected with each horizontal scan. This is 525 times each revolution at 1800 rpm, producing a very accurate disk-frame rate synchronization.

In the recorders that provide sync signals to control the television camera scanning, the disk is rotated by a synchronous motor. The motor design and the relatively high angular moment of the disk produce a nearly constant rotation. A separate magnetic track and playback head provide a pre-recorded sync signal that is processed into standard TV sync pulses for the camera chain. For any instantaneous speed variation, the time nstability occurs in both the sync signal and the recorded frame. Thus, synchronization is maintained on playback and the frame appears essentially the same as originally recorded. The pre-recorded sync technique is preferable to servo-control because of simplicity, reliability, and economy. However, the camera chain must be designed for compatible operation and another source of sync signals must be available in case the recorder fails or is not used.

Both types of recorder were tested with the electronic radiography system. All operated satisfactorily and produced acceptable imaging. However, the servo-controlled recorder tested has the simplest type of

speed control and cannot consistently provide the desired rotational stability. According to the manufacturer's specifications, this recorder has a time base stability of ± 150 nanoseconds between horizontal sync pulses. If this error happened to accumulate throughout a frame, the total error would be: 150 nanoseconds/line x 525 lines/frame = 78,750 nsec/frame, or 78.75 microseconds/frame. This is greater than the 63.5 microseconds required for one television line. The phase relation between the horizontal sync and a stable sync would then vary more than 360° during one frame, introducing an instantaneous horizontal phase shift at the splice point where a recorded frame begins and ends. On playback, the horizontal automatic frequency control (AFC) in a monitor would interpret this shift as a frequency error in the monitor and try to correct the error. If the AFC has a long time-constant, with consequent slow reaction to a sudden phase shift, the two television fields will be horizontally displaced from each other and appear as a double exposure. If the time constant is short, the AFC will react quickly, but "hunt," causing one or both fields to appear distorted. Even if the AFC is critically damped, there will be some interfield displacement at the top half of the image and an annoying interfield flutter.

Two recorders of the type providing sync drive for the camera chain were tested. One provided industrial sync to EIA RS-330 specifications (*64*), but the camera chain required commercial EIA RS-170 sync (*63*). This mismatch caused considerable technical difficulty in obtaining proper operation of the camera. When the system performed properly, however, the image quality was excellent. The other recorder, in the Westinghouse system, was supplied with a compatible camera chain and presented no technical difficulties. The image quality was also excellent. All three recorders have similar performance characteristics: horizontal resolution is about 330 TV lines, signal-to-noise ratio about 40 db, and differential gain about 10 percent. These values are similar to the standards required of commercial television broadcasters in the United States. The servo-controlled recorder tested also operates satisfactorily with either industrial or commercial sync. All recorders tested are capable of meeting the technical requirements of an electronic radiography system.

3.4 ELECTRONIC (NON-MECHANICAL) VIDEO MEMORY

The mechanical problems encountered with magnetic disk recording led to an investigation of alternate means of storing single-frame television images. Non-mechanical digital storage techniques seemed capable of overcoming the disadvantages of mechanical recorders. Although no non-mechanical digital storage system for video recording exists, the state of the art provides the essential elements for evaluation of two techniques: digital magnetic core memory, and digital recirculating delay line memory.

At this time the expense of any non-mechanical digital system with a storage capability equivalent to the magnetic disk is prohibitive. Therefore, the relatively inexpensive analog image storage tube, which was not considered initially because of operational limitations, was evaluated along with the two digital techniques. The advantages and disadvantages of each technique were examined and compared with analog magnetic disk recording. Each of the three methods is technically capable of producing an adequate image with quality, resolution, and cost dependent on the selected digital bit storage capacity, or bandwidth. For comparison purposes, all were considered as operating with the monochrome television broadcast standard of 525 lines per frame and 30 frames per second of two fields interlaced 2:1; and a 4.2 MHz bandwidth for a resolution of about 340 by 340 TV lines.

3.4.1 *Image Storage Tubes*

Television image storage tubes are available with a variety of characteristics. Some are directly-viewed cathode-ray tubes. Others combine direct viewing with an electronic readout for viewing on a standard television monitor. Some have only electronic readout. All are potentially applicable to electronic radiography, but have limited image storage and viewing times. Resolution, contrast, and gray scale capabilities vary with design and price. The use of image storage tubes in radiography was mentioned in section 2 of this report; Wallman and Wickbom (*36*) employed a direct-view tube, while Berci (*42*) used a direct-view tube with electronic readout.

Early image storage tubes were relatively costly, sometimes poor in contrast and resclution, and often critical in electrical adjustment and operation. Modern direct-view tubes offer somewhat better contrast and resolution, but still have a short image storage time (about 5 minutes) and viewing time (about 10 seconds). With a perfect noise-free input signal, the best direct-view tubes are capable of displaying seven shades of gray, with a resolution of 400 TV lines and a contrast ratio of 3.5:1. The electronic circuitry is similar to that of a standard TV monitor. The direct-view tube can provide instantaneous TV image storage and display more economically than any other memory device.

Direct-view storage tubes with electronic readout present a small viewing area (about a 4-inch square), whereas electronic readout permits large-screen viewing on standard monitors, with control of brightness and contrast. Viewing time is about 30 seconds for direct viewing and somewhat greater when using electronic readout and viewing on a monitor.

Storage tubes with electronic readout only and no viewing screen are superior in performance. They have been developed to a high degree of perfection for television scan conversion, slow scan transceivers, and radar memory applications. A typical tube of this type with a silicon

storage target (*69*) has a resolution of 900 TV lines, full gray scale, a storage time of several hours and viewing time of several minutes. High performance tubes are also available with resolution capabilities of 2,000 TV lines; these are very expensive.

Compared with the mechanical magnetic disk recorder, analog storage tubes offer a wide selection of performance and price, require only simple electronic adjustments, and are stable in operation; also, they have no moving parts. However, they can store only one image at a time, while a video disk can be obtained to store 1,000 images for an unlimited time with no deterioration. Prices range from $5,000 to $25,000 for disk recorders and $2,500 to $25,000 for storage tubes, depending on performance and manufacturer. The resolution capability of a high-performance storage tube is greater than that of the magnetic disk, but the gray-scale capability is usually less.

3.4.2 *Digital Storage Systems*

A digital magnetic core or digital recirculating delay line memory requires digitization of the analog video signal before storage and reconversion of the stored information for playback on a television monitor (figure 12). The digital storage capacity must be at least one million bits to reproduce a single television frame with a quality similar to that reproduced with an analog magnetic disk recorder.

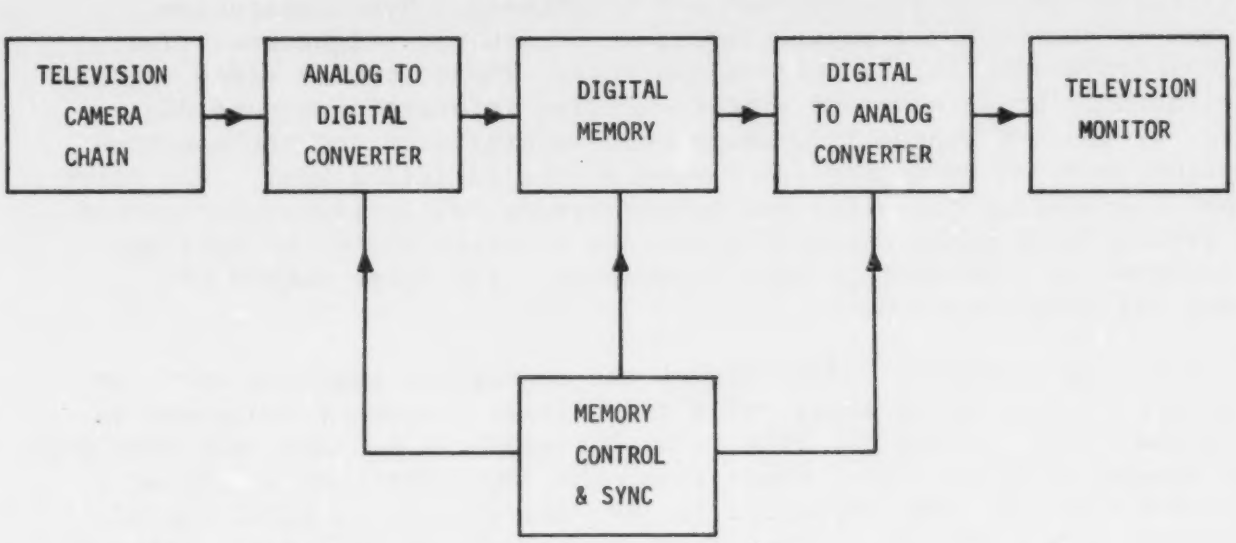

Figure 12. Simplified block diagram of a digital TV image storage system.

Digital image storage also has limitations similar to those of analog storage. The resolution and gray scale depend upon the number of digital bits used to represent the image information, just as they depend on the bandwidth of an analog system. The accuracy of digital representation is limited and determined by the number of bits making up the digital word. For example, if a 6-bit digital word is used, the video signal amplitude can be represented by one of only 64 discrete values. For a signal of 1-volt peak-to-peak maximum, the 64 possible amplitude levels would be spaced 0.016 volts apart.

The use of more bits per word increases the accuracy of digitization, but also increases the required storage capacity; since the time required for image storage is fixed at 1/30 second by the television system, the data transfer rate must also increase. Thus the number of bits that can be used is limited by the storage capacity and data transfer rate of currently available digital memory systems. The required number of bits, storage capacity, and transfer rate will be less if brightness information is restricted. If digital word representation is restricted to an extreme of 1-bit, image quality will suffer severe contouring and complete loss of gray scale. With 3 bits, gray scale will be severely limited. Six-bit representation will produce an image equivalent to the original monochrome television image.

In a 1-volt video signal, information regarding brightness of the picture elements is carried in the range of 0.3 to 1.0 volt, and synchronization in the range of 0 to 0.3 volt. Each picture element is specified by stating its position and brightness. Synchronization determines position and signal amplitude determines brightness. The digital conversion may be done in two ways: The composite video signal carrying both brightness and synchronization information can be digitized; or the brightness information can be digitized and the synchronization conveyed by controlled timing of the digital signal. The first method has simpler circuitry and better timing reliability. The second has greater gray scale capability because a larger number of bits may be assigned to represent picture brightness. The first method was chosen for investigation.

In digitizing an analog signal the conversion sampling rate, or frequency, should be at least twice the highest frequency contained in the signal (*68*). Since the television bandwidth is 4.2 MHz, the sampling rate should be at least 8.4 MHz. Thus, the converter must sample at a rate of 8.4×10^6 samples/second for the frame duration (1/30 second) and assign 2.8×10^5 binary numbers to represent one TV frame. Using 6 bits/word would require storage of 6 times 2.8×10^5 or 1.68×10^6 bits/frame, and a data transfer rate of 8.4×10^6 times 6, or 50.4M bits/sec. Analog-to-digital and digital-to-analog converters with these capabilities are commercially available (*68*). Their performance is adequate for even higher television scan rates and resolutions than required for electronic

radiography and can exceed the gray scale capabilities of the television system. A color television image produced by 7-bit digital transmission is equivalent to a commercial color broadcast in clarity, color and fidelity (*68*).

3.4.3 *Recirculating Delay Line Memory*

The recirculating delay line memory functions by continuously recirculating the digital information through a time delay equal to the duration of 1 TV frame, or 1/30 second. The required data transfer rate depends on the conversion rate of the analog-to-digital converter; it would be 50.4M bits/sec. at 6 bits/word. The 1-frame delay of 1/30 second must be extremely stable or synchronization will be impossible. Of the several materials used for delay lines, only zero-temperature-coefficient glass approaches these requirements. The delay is stable, but the required data transfer rate can be achieved only by using a number of delay lines operating in parallel (figure 13) (*65*). Each bit of the digital representation is then assigned to a separate bank of parallel delay lines.

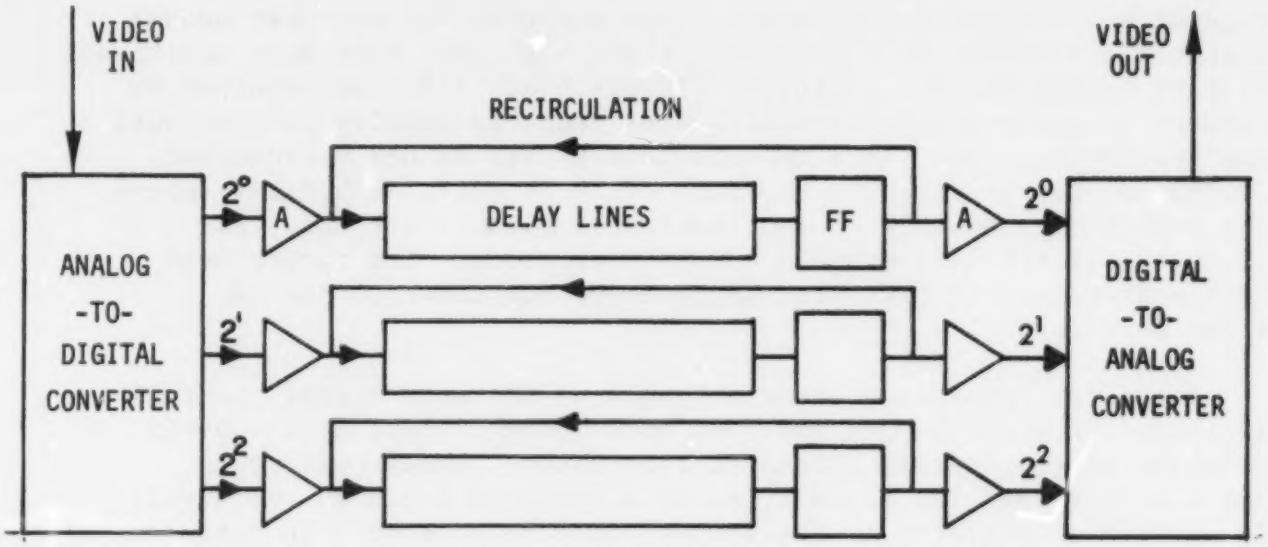

Figure 13. Simplified block diagram of recirculating delay line video memory for 3-bit digitization. (A = amplifiers and FF = flip-flops)

Delay lines of zero-temperature-coefficient glass construction are commercially available with a maximum delay of 256 microseconds and maximum transfer rate of 8.4M bits/sec. (*66*). A 1-frame TV memory using banks of these delay lines would require 131 individual delay lines per bit to attain the 1/30 second delay. A 4-bit system would require 524 delay lines, and 786 lines would be needed for a 6-bit system. In these quantities, delay lines cost about $100 each. A complete 6-bit system would thus cost $80,000 to $100,000. Size, weight, and heat dissipation would be prohibitive for use in an electronic radiography system. For the recirculating delay line memory to be practical, individual delay lines with a significantly longer delay time must be developed.

The storage time of a recirculating delay line memory would be virtually unlimited, since the digital signal is continuously regenerated. Any interruption in the operation, however, would destroy the stored information. Artifacts, such as transient noise, which exceed the input threshold would also be included in the stored image. Because of the electromagnetic environment, such artifacts would in time impair the quality of the stored image.

3.4.4 *Magnetic Core Memory*

Magnetic core memories of the computer type may also be used for storage of a digitized video image. Core memories are not fast enough to accept the required data transfer rates; also they must have additional short-term buffer storage registers (figure 14). The time required by the memory to store a digital word and be ready to receive another word is the full cycle time. In a typical memory this is one microsecond. The required storage capacity and data transfer rate, as before, depend on the number of bits used to represent each picture element. For a 6-bit system (1.68M bits/frame at 50.4M bits/second) the memory must store approximately 50 bits each microsecond for the 1/30 second TV frame duration.

A typical memory can store a single 48-bit word during the full cycle time. In order to utilize this word length, eight of the 6-bit words would be temporarily stored in a register. These would then, during 1 microsecond, be transferred to a group of cores as one 48-bit word. A similar register in the output would be necessary to reconvert the 48-bit word to the eight 6-bit words, for digital-to-analog conversion and TV image display. In order to represent 1 TV frame of about 1.5M bits, sufficient core groups would be required to store at least 32,000 of the 48-bit words. A memory organized in a 32K x 48 configuration, with a full cycle time of 1 microsecond, is readily available (*67*); input and output storage registers can be constructed with little difficulty.

Magnetic core memories are presently priced at $0.05 per bit. The cost of a complete 32K x 48 memory is about $80,000; complete system cost would be about $100,000. A core memory does not require regeneration of the stored information as does a delay line memory. In fact, the stored data will remain for any length of time with the power removed. Bit storage is achieved by magnetization of individual cores and considerable energy is required to produce a change in magnetization. Hence, extraneous electromagnetic artifacts are not likely to contaminate the image. Also, no routine maintenance is required and the possibility of failure is remote.

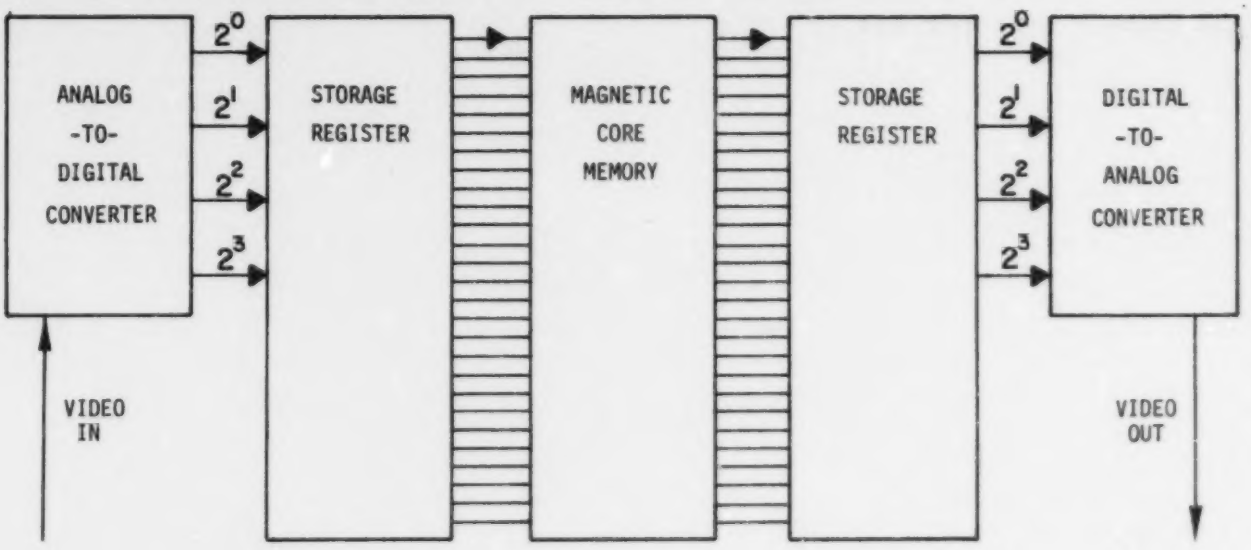

Figure 14. Simplified block diagram of magnetic core video memory for 4-bit digitization.

3.4.5 *Summary*

It is important to note that selection, complexity, and cost of any digital storage system will depend on the total number of bits and the bits/word used for image representation; this number is determined by the gray scale needed to produce the desired image quality. The quality (signal-to-noise ratio) selected for the radiographic image is dependent on many factors, as discussed in appendix A.

The cost of digital memories will probably decrease as solid-state technology advances and component production costs decline. It has been estimated that within the next 10 years magnetic core memories will be available for about one-fourth present cost. Recent innovative techniques such as laser-generated optical memories and the Bell Laboratories "magnetic bubble" memory may become practical, with predicted costs of less than 1 cent per bit.

4. CLINICAL EVALUATION

In planning the clinical trials, a careful attempt was made to select procedures for which electronic radiography has the potential to provide adequate diagnostic information while affording a large reduction in dose to critical organs. Since the primary aim of the project was to appreciably reduce exposure incident to x-ray examination, the initial clinical trials were performed using the least possible x-ray photon rate/time product to obtain an image. This limited the possible areas of clinical acceptance, and tended to discourage a few radiologists accustomed to relatively "high-quality" images. In most instances, however, the images offered sufficient information to meet the intended clinical objective, such as visualization of catheter position, bone structure, gastrointestinal segments, and ureteral reflux. In any case, the x-ray input could be increased with proportionate increase in "quality" of the stored image until the resolution limit of the image intensifier is reached (see section 3 of this report). Initially there was concern that image displays at the rate of 1 to 5 per second would be objectionable and tiresome to the observer, especially in instances of substitution for fluoroscopy. Under actual clinical conditions, sequence imaging at these rates proved to be quite acceptable.

Admittedly, presenting a written description of visual impressions gained in the preliminary clinical trials is most difficult. The trials clearly established, however, that electronic radiography can readily replace continuous fluoroscopy during certain phases of an examination. Where the fluoroscopist must reorient himself with the depicted anatomical structures during each viewing period, electronic radiography saved several seconds of exposure by retaining the last image viewed. At this time electronic radiography cannot be regarded as a direct replacement for all radiographic or fluoroscopic techniques, but rather as a valuable adjunct to these radiologic modalities.

From the radiologist's point of view, electronic radiography offers two distinct advantages over conventional fluoroscopy and spot film radiography: reduction in occupational and patient radiation exposure, and production of an instantly available x-ray image for interpretation. Obviously, the resulting degree of exposure reduction varies with the type of radiologic examination and is influenced by the subjective impressions of individual radiologists.

With expected improvements in the resolution of image intensifiers, optical coupling, and television systems, further progress in the clinical application and usefulness of electronic radiography is anticipated. An electronic radiography system in an operating room could markedly reduce the x-ray exposure and time required for surgical procedures where film

radiography is now employed, such as orthopedic manipulations and operative cholangiography. In the future, a photograph of an electronic radiograph might serve as a permanent record in such cases, eliminating film radiography.

4.1 CARDIAC CATHETERIZATION

Of the several clinical applications investigated, the electronic radiography system was tested principally in conjunction with fluoroscopic examinations coincidental to catheterization of the heart and great vessels. Studies of patient x-ray exposure incident to these procedures were performed over a period of 2 years. During this period, exposure values were recorded on a series of cardiovascular procedures before and after installation of the electronic radiography system. Two different conventional fluoroscope setups were studied during the accumulation of data before use of electronic radiography. The first was a single-phase fluoroscopic x-ray generator and Philips 6-inch image intensifier with vidicon television viewing, referred to as system A. The second, referred to as system B, was identical except for installation of a new x-ray tube and realignment of the television camera chain for optimum operation both optically and electronically. A comparison of patient exposure values in each situation is shown in table 1.

After accumulation of base-line patient exposure data using conventional image intensification and television viewing, the electronic radiography system was placed in service with system B. This combination, referred to as system C, provided the physician a choice of using electronic radiography or fluoroscopy. Following 2 weeks of testing and physician experience with electronic radiography, comparative patient exposure data were accumulated using system C during routine cardiac catheterization. These results are shown in table 2. All procedures, on all systems, were performed by physicians under the supervision of the director of the cardiac catheterization laboratory.

4.1.1 *Fluoroscopic Exposure Comparisons*

The exposure comparisons were made using eight selected age groupings to encompass all patients. The youngest was 4 days and the oldest 69 years. The age range for each group was modified from that suggested by the ICRP/ICRU (*14*) on the basis of weight, chest thickness, and x-ray machine factors (R/min). The most distinctive criterion in the selection of exposure rate appears to be weight, until the age of about 17 years. Above age 17 there is an apparent tendency to use higher kVp for patients in the older age groups, which also average slightly greater chest thickness.

Table 1. Comparison of patients (average weight and chest thickness) and exposure from fluoroscopy during routine cardiac catheterization using two different x-ray equipment setups (Systems A and B).

Age range	System	No. of patients	Avg. kVp	Avg. wt. (lbs)	Avg. chest thickness (cm)	Avg. exp. time (min)	Avg. exp. rate (R/min)	Avg. exp. (R)	Avg. SEI[1] ($R\text{-}cm^2$)
0-6 mo	A[2]	3	70	7.4	7.7	28.0	0.111	3.1	249
	B[3]	5	66	8.9	8.0	16.0	0.094	1.5	120
7 mo-2 yr	A	10	77	18.9	10.3	29.5	0.170	5.0	402
	B	8	71	19.3	10.1	47.2	0.151	7.1	570
3-5 yr	A	10	79	37.7	12.0	24.3	0.203	4.9	394
	B	17	75	35.3	11.3	26.3	0.161	4.2	338
6-10 yr	A	5	82	55.8	14.1	26.4	0.300	7.9	633
	B	14	80	57.9	13.5	28.4	0.366	10.4	832
11-16 yr	A	4	85	117	17.1	35.4	0.632	22.4	1792
	B	14	84	102	16.3	27.7	0.522	14.5	1160
17-36 yr	A	18	93	130	19.3	30.7	0.978	30.0	2400
	B	16	90	129	19.2	27.1	0.705	19.1	1528
37-56 yr	A	9	97	141	21.0	48.6	1.34	65.1	5208
	B	8	94	124	19.0	48.3	0.913	55.3	4424
57 yr and up	A	1	100	109	19.0	39.8	0.530	21.1	1688
	B	1	90	120	18.0	19.2	0.550	10.6	848
ALL	A	60	85			32.1	0.638	20.5	1640
	B	83	81			30.5	0.433	13.2	1056

[1]SEI: surface exposure integral
[2]System A: single-phase fluoroscopic x-ray generator and 6-inch image intensifier with vidicon TV viewing
[3]System B: identical to A except for installation of new x-ray tube and realignment of TV camera chain for optimum operation

Table 2. Comparison of patients (average weight and chest thickness) and exposure values resulting from fluoroscopy only (System B) and fluoroscopy with electronic radiography (System C) during routine cardiac catheterization.

Age range	System	No. of patients	Avg. kVp	Avg. wt. (lbs)	Avg. chest thickness (cm)	Avg. exp. time (min)	Avg. exp. rate (R/min)	Avg. exp. (R)	Avg. SEI[1] (R-cm^2)
0-6 mo	B[2]	5	66	8.9	8.0	16.0	0.094	1.5	120
	C[3]	9	66	8.8	7.8	23.8	0.110	2.6	209
7 mo-2 yr	B	8	71	19.3	10.1	47.2	0.151	7.1	570
	C	13	76	20.3	10.1	28.0	0.170	4.8	380
3-5 yr	B	17	75	35.3	11.3	26.3	0.161	4.2	338
	C	18	80	32.5	11.6	23.8	0.180	4.3	342
6-10 yr	B	14	80	57.9	13.5	28.4	0.366	10.4	832
	C	16	82	53.5	12.8	19.5	0.380	7.4	592
11-16 yr	B	14	84	102	16.3	27.7	0.522	14.5	1160
	C	23	88	99	15.5	25.8	0.761	19.6	1568
17-36 yr	B	16	90	129	19.2	27.1	0.705	19.1	1528
	C	12	91	134	18.3	19.9	0.980	19.5	1560
37-56 yr	B	8	94	124	19.0	48.3	0.913	55.3	4424
	C	6	93	147	20.5	24.3	1.27	33.5	2680
57 yr and up	B	1	90	120	18.0	19.2	0.555	10.6	848
	C	4	95	134	17.0	36.3	1.20	43.6	3488
ALL	B	83	81			30.5	0.433	13.2	1056
	C	101	84			24.2	0.537	13.0	1040

[1]SEI: surface exposure integral
[2]System B: conventional fluoroscopy-same as system B in table 1
[3]System C: system B, plus electronic radiography system, at user option

In the comparisons between system B (conventional fluoroscopy only) and system C (electronic radiography or conventional radiography, at user's option) a decrease in average exposure would be expected for system C because of the potential decrease in average exposure time for groups of similar-sized patients. However, table 2 shows a significant decrease in time in only four age groups: 7 mo-2 yr, 6-10 yr, 17-36 yr, and 37-56 yr. An increase in time occurred in two age groups: 0-6 mo and 57 yr and up. The data for the 57 yr and up category are not conclusive because of the small number of cases. The overall results indicate no significant decrease in exposure for system C. Because the user was offered a choice of fluoroscopy and/or electronic radiography during routine cardiac catheterization, apparently the physicians were not stimulated to reduce their use of fluoroscopy to the desired degree.

4.1.2 *Cineradiography Exposure*

In addition to the fluoroscopic exposure in cardiac catheterization, there is the exposure from cineradiography of the infusion of contrast media into the vessels and chambers of the heart. Although this phase of the examination is of short duration as compared with the fluoroscopy, the x-ray rate must be considerably increased in order for the intensifier screen to provide sufficient light to expose the cine film. Often the total exposure from cine recording is greater than that from fluoroscopy. A comparison of the fluoroscopic (F) and cineradiographic (C) exposure for the 101 cases performed using system C is shown in table 3. Even if electronic radiography could completely replace fluoroscopy in heart catheterization, there would remain the x-ray exposure required for cineradiography. Replacement of cine with video tape recording could eliminate x-ray exposure rate for cine is approximately 30 to 40 times that required for fluoroscopy. In preliminary trials at the Emory University Department of Radiology, television recordings provided images comparable to cine, with x-ray rates of only two to four times that of fluoroscopy.

4.1.3 *Electronic Radiography*

The range in number and x-ray exposure of electronic radiographs for each age group is shown in table 4, together with the exposures for fluoroscopy and cine radiography. The exposure time for an individual electronic radiograph ranged from 1/30 to 1/5 second, using the fluoroscopic factors established for each case (table 2). The minimum exposure for a single electronic radiograph was approximately 0.2 mR on an infant. Such a low exposure produces a quantum-limited image, but the catheter position is discernible. Most electronic radiographs resulted in an exposure of 0.5 to 1 mR per image for children, and 1 to 4 mR per image

Table 3. Comparison of the fluoroscopic (F) and cineradiographic (C) exposure values for the 101 cases performed with System C, table 2.

Age range	Type of Exp.	No. of patients	Avg. kVp	Avg. wt. (lbs)	Avg. chest thick-ness (cm)	Avg. exp. time (sec)	Avg. exp. rate (R/sec)	Avg. exp. (R)	Avg. SEI* ($R-cm^2$)
0-6 mo	F	9	65	8.8	7.8	1438	0.002	2.62	209
	C		68			67	0.060	4.0	320
7 mo-2 yr	F	13	75	20.3	10.1	1680	0.003	4.76	380
	C		73			53	0.111	5.9	472
3-5 yr	F	18	75	32.5	11.6	1438	0.003	4.28	342
	C		73			50	0.121	6.1	488
6-10 yr	F	16	85	53.5	12.8	1170	0.006	7.41	592
	C		85			50	0.238	11.9	952
11-16 yr	F	23	90	99	15.5	1548	0.013	19.6	1568
	C		92			62	0.497	30.8	2460
17-36 yr	F	12	90	134	18.3	1194	0.016	19.5	1560
	C		95			52	0.614	31.9	2550
37-56 yr	F	6	90	147	20.5	1548	0.021	33.5	2680
	C		96			50	0.647	32.4	2590
57 yr and up	F	4	95	134	17.0	2178	0.020	43.6	3488
	C		101			40	0.612	24.5	1960
ALL	F	101				1452	0.009	13.0	1040
	C					53	0.363	19.2	1536

*SEI: surface exposure integral

Table 4. Range in number and value of exposures for the electronic radiography, performed in conjunction with fluoroscopy and cineradiography, in the 101 cardiac catheterizations with System C, table 2.

Age group	No. of patients	Electronic radiography			Fluoroscopy		Cineradiography	
		No. of exposures	Total exp. time (sec)	Total exp. (mR)	Avg. exp. time (min)	Avg. exp. (R)	Avg. exp. time (sec)	Avg. exp. (R)
0 - 6 mo	9	12 - 65	1.4 - 7.8	2.5 - 14	23.8	2.6	67	4.0
7 mo- 2 yr	13	7 - 150	0.8 - 18	2.3 - 51	28.0	4.8	53	5.9
3 - 5 yr	18	8 - 68	1. - 8.2	3. - 25	23.8	4.3	50	6.1
6 - 10 yr	16	7 - 59	0.8 - 7	5. - 44	19.5	7.4	50	11.9
11 - 16 yr	23	9 - 85	1.1 - 10	14. - 127	25.8	19.6	62	30.8
17 - 36 yr	12	13 - 81	1.6 - 9.7	26. - 147	19.9	19.5	52	31.9
37 - 56 yr	6	9 - 43	1.1 - 5.2	23. - 110	24.3	33.5	50	32.4
57 yr and up	4	4 - 56	0.5 - 6.7	10. - 134	36.3	43.6	40	24.5
ALL	101	4 - 150	0.5 - 18	2.3 - 147				
AVERAGE		30	3.6	32	24.2	13.0	53	19.2

for adults. Figure 15 is a photograph of a typical electronic radiograph recorded during cardiac catheterization of a child. The image adequately demonstrates location of the catheter tip in the right main pulmonary artery with an exposure of 1 mR to the patient. The x-ray rate/time product was purposely maintained as low as possible. A better image could be obtained at any time by increasing exposure, but this was not necessary in most cases.

NOT REPRODUCIBLE

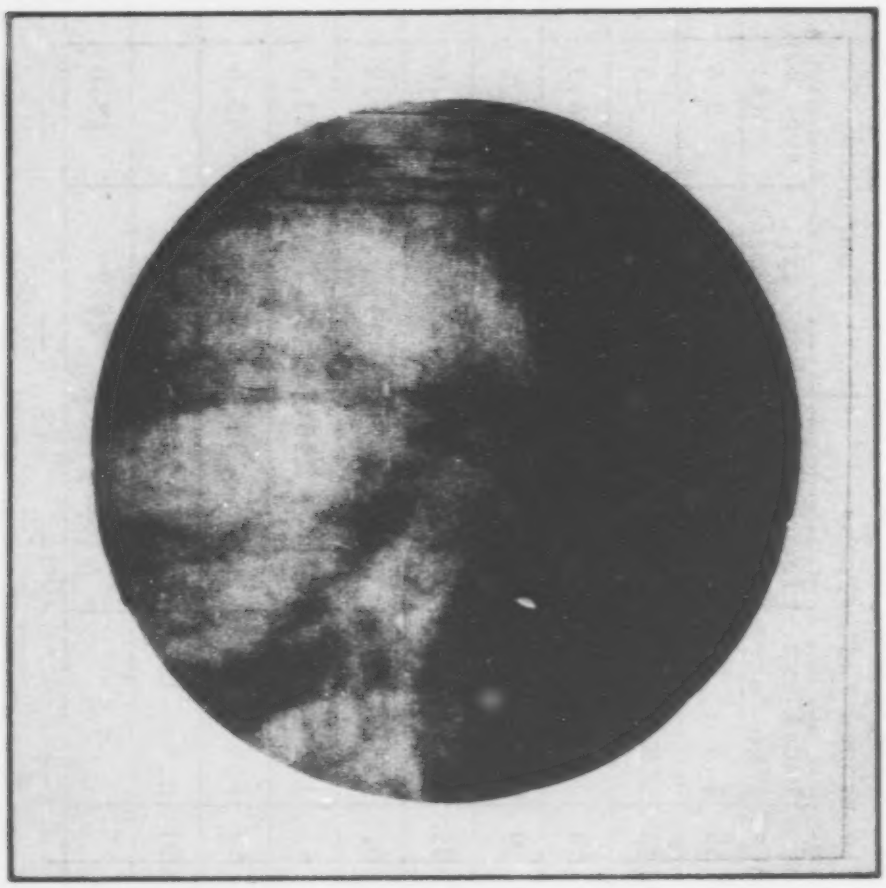

Figure 15. Electronic radiograph demonstrating catheter tip in the right main pulmonary artery of a child. The exposure, kept as low as possible, was 1 mR to the patient.

Even though the expected reduction in fluoroscopic exposure was not attained during the trials, important side benefits of special value became apparent in certain situations. Use of electronic radiography for the study of complex congenital anomalies in young infants provided a more precise diagnosis at the time of the study, eliminating the need for repeated examinations which result in additional exposure and the hazard of larger doses of contrast media. These advantages also exist for other examinations, such as coronary angiography where one quick fluoroscopic glimpse is inadequate for studying the detail of the injected artery.

The stored image of electronic radiography is of value for comparing catheter position at various times to reveal any change in location. For example, in using a balloon catheter, pressures are sometimes not available or unreliable, and catheter position is very important. Experience has also shown that in placement of a catheter electrode for cardiac pacing, fluoroscopic exposure times frequently far exceed those of cardiac fluoroscopy. The use of electronic radiography for this procedure affords an appreciable reduction in fluoroscopy time and radiation exposure to both patient and personnel.

4.1.4 *Other Considerations*

The cardiac procedures of the clinical trials encompassed the full range of congenital and acquired disease in infants, children, and adults, exclusive of adult coronary arteriography. Among the 101 cases (system C) there were approximately 30 different disease conditions, including anomalies, combinations of conditions, and postoperative studies. Observation of the procedures and discussion with the physicians over a long period of time did not reveal any outstanding patient factor that might predictably influence the x-ray exposure. In most cases x-rays were used conservatively, but to the extent necessary to obtain the desired diagnostic or postoperative information.

During these procedures, the x-ray target was positioned 20 inches beneath the tabletop, and the beam circularly collimated not to exceed 6 inches in diameter at the input plane of the image intensifier. The x-ray generator had no provision for automatic control of kVp or mA. The fluoroscopic factors were established for each case by an x-ray technician, based on experience and adequate visualization. The cine factors were based on a metered indication of average intensifier brightness. The fluoroscopic factors were not often changed during a procedure; any changes that did occur were carefully noted on the patient data record. In the cineradiography, which usually involved several patient positions, the x-ray factors and exposure times were recorded for each position. The values of cine exposure rate and total exposure (tables 3 and 4) were determined by weighting the values for each patient position with regard to the corresponding machine factors and exposure times.

The Surface Exposure Integral (an index value of intensity and distribution of exposure, expressed in terms of R-cm^2) in tables 1 through 3 was calculated for each age group from the average exposure and maximum possible surface exposure area of 83 square centimeters established by the circular collimation of the beam. The values of x-ray tube current for fluoroscopy varied from about 1/10 to 2 mA and were determined using a low-range milliammeter of about 10 percent accuracy installed especially for the studies. The readings were correlated with the x-ray machine calibrations for reproducibility of exposure rates rather than for determination of true tube current.

For comparative purposes, the half-value-layer (HVL) was determined for each major kVp setting:

kVp	HVL (mm Al)
60	1.95
70	2.35
80	2.65
90	3.0
100	3.3
110	3.55

For all clinical trials the x-ray exposure values were measured at the tabletop and frequently rechecked using an NBS-calibrated Victoreen condenser R-meter and cross-calibrated Victoreen "Radicon" ratemeter.

4.2 RENAL BIOPSY

The custom in the Emory University Department of Radiology is to obtain renal biopsies using fluoroscopy in conjunction with intravenous urography. Utilizing electronic radiography, a renal biopsy has been performed with as little as 47 mR of tabletop exposure for the complete examination. In this case, thirty television images of 1/60 second x-ray exposure each were obtained, of which figure 16 is an example. The total radiation exposure was equivalent to about 0.5 sec of fluoroscopy at 100 kVp and 4 mA.

NOT REPRODUCIBLE

Figure 16. Image stored during renal biopsy procedure, confirming adequate placement of biopsy needle. Note outline of lower pole of kidney and ureter. Exposure was approximately 2 mR.

4.3 CYSTO-URETHROGRAPHY

Electronic radiography has obvious advantages in pediatric radiology, for gonadal exposure should be kept as low as feasible. In a small group of both normal and pathologic cysto-urethrography procedures, electronic radiographs acquired at selected rates of 1 to 2 per second were produced with x-ray exposures of 1/30 sec at 95 kVp and 0.1 to 0.5 mA. The total patient exposure per procedure was the equivalent of 3 to 24 seconds of fluoroscopy, with "spot film" radiography completely eliminated. The sequential images are stored on the magnetic disk recorder for later display and photographing. The photographs were

acceptable to both urologists and internists. Transient ureteral reflux could be demonstrated in the individual images, as shown in figure 17. In this case, the reflux could have been missed with conventional film technique unless continuous fluoroscopy were employed throughout the entire procedure.

NOT REPRODUCIBLE

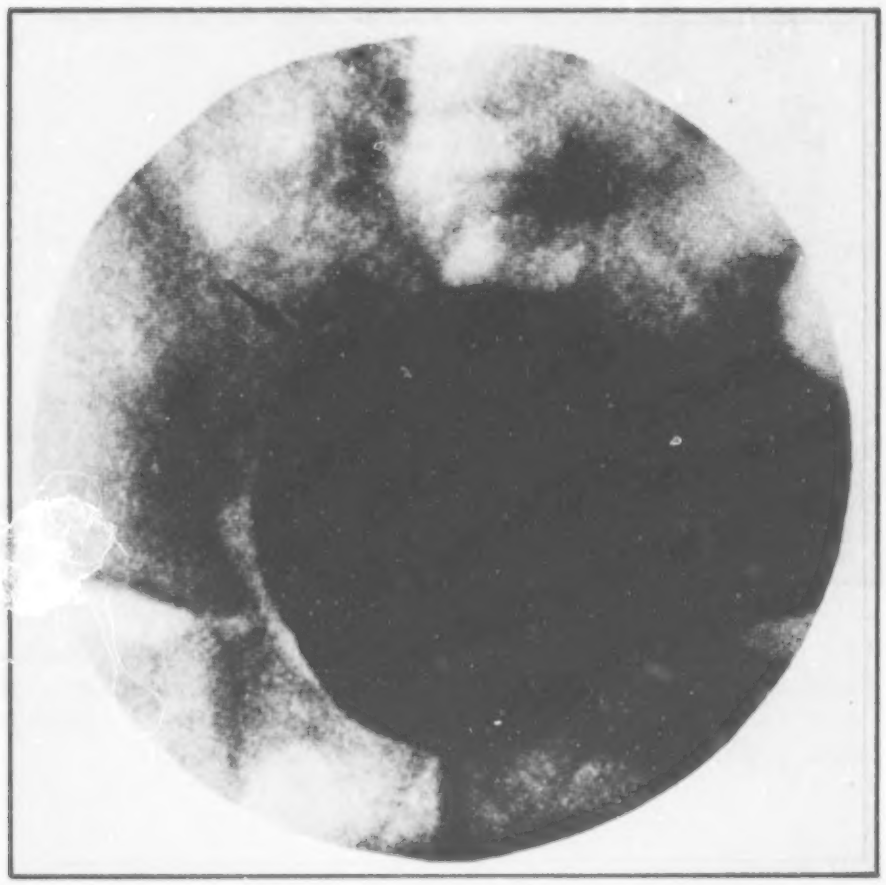

Figure 17. One of a sequence of images obtained during voiding cystogram on child with bilateral ureteral implantation. Transient right reflux was minimal (arrow). Exposure was approximately 1 mR.

4.4 ORTHOPEDICS

An example of the resolution available for orthopedic work is shown in figures 18 and 19. Figure 18, an electronic radiograph taken through a cast, represents the wrist of a patient with severe rheumatoid arthritis. Most of the carpal bones had been destroyed and surgical excision of the distal ulna performed. This image was obtained with a minimal exposure of 0.75 mR. Figure 19 depicts a hip joint taken with an increased exposure of approximately 6 mR for quality comparison. Fracture manipulations performed using electronic radiography have proved to be valuable because of the low radiation exposure and ready availability of the images. At the present time, however, the viewing area of the image intensifier (5 inches) restricts to some extent the determination of long bone angulation.

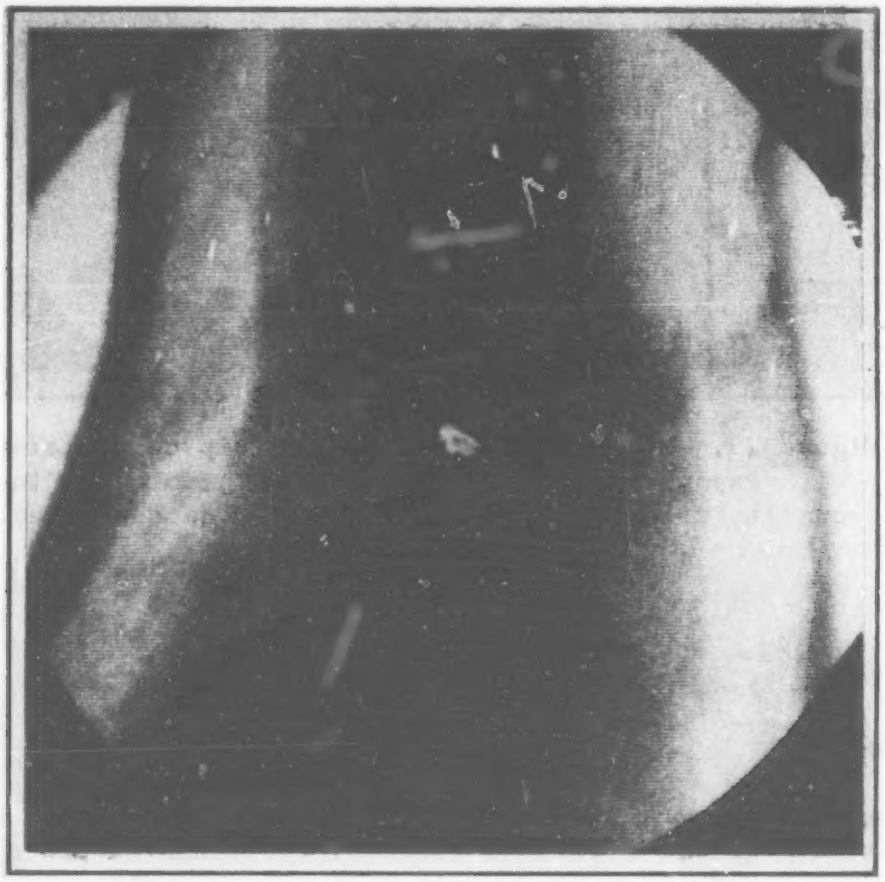

Figure 18. Electronic radiograph of wrist joint of patient with severe rheumatoid arthritis. This image, taken through the cast with only 0.75 mR, adequately demonstrates position of long bones and metal pins.

NOT REPRODUCIBLE

NOT REPRODUCIBLE

Figure 19. Electronic radiograph of hip joint taken with exposure of approximately 6 mR. Increase in quality with increase in exposure is demonstrated.

4.5 GI SERIES

Although continuous fluoroscopy is a generally-accepted method for the study of the gastrointestinal tract, intermitten sequence imaging can provide useful information equivalent to continuous fluoroscopy. For instance, with certain segments of the gastrointestinal tract characterized by little motility, barium enema examinations using 1 or 2 images per second can provide adequate information concerning the flow of contrast medium.

In the comparison of the exposure values for upper GI examinations, shown in table 5, use of electronic radiography afforded a reduction of 80 percent in the average exposure for the fluoroscopic phase of the examination. Clinical trials of electronic radiography in gastrointestinal examinations are continuing and will be discussed further in a future report. Figure 20 depicts an electronic radiograph obtained during a gastrointestinal examination with a radiation exposure of about 8 mR.

Table 5. Comparison of conventional fluoroscopy and electronic radiography in routine upper GI examinations of similar cases

	Conventional fluoroscopy	Electronic radiography
No. of exams	20	20
Avg. peak potential (kV)	91.7	87.6
Avg. current (mA)	1.2	0.56
Avg. time (min)	5.16	2.46
Avg. exposure/exam (R)	20.4	4.13

A comparison of representative exposure values for conventional versus electronic radiography in selected procedures is shown in table 6. This includes one hysterosalpingography successfully performed with a patient exposure equivalent to less than 2 seconds of fluoroscopy.

4.6 OTHER TRIALS

Electronic radiography has also been successfully used in fetal intrauterine transfusion. As an investigative tool, it is presently being used in an analysis of hip dislocation and excessive anteversion of the femoral neck in a group of patients with spastic cerebral palsy. With the first 21 patients, adequate imaging was obtained with total exposures ranging from 2 to 10 mR for each examination consisting of several projections.

NOT REPRODUCIBLE

Figure 20. Electronic radiograph of distal stomach and duodenum. Exposure was approximately 8 mR.

4.7 TRAINING

The type and level of training required by physicians in the various specialties to use electronic radiography is similar to that for conventional radiographic techniques and equipment. If the potential user is familiar with radiographic techniques, approximately 15 minutes of on-the-job training is sufficient to obtain proper equipment performance. In order to realize the maximum benefits of the system, however, one to two hours of training from a physicist or engineer is desirable. This instruction should include a review of x-ray imaging and the physical principles of televised image intensification plus techniques of TV image storage (as discussed in sections 2 and 3 of this report).

If the system is considered as a special-purpose device, with the x-ray output limited and exposure time preset, the potential radiation hazard is much less than that of a fluoroscope with TV viewing of the image intensifier. Such a device might be most suitable for use by specialists outside the field of radiology.

Table 6. Representative exposure values for selected x-ray procedures, conventional vs. electronic radiography technique

Exam. type	Conventional fluoroscopy plus film radiography							Electronic radiography					
	Fluoro.			Film			Exp. (R)	No. Cases	kVp	mA	No. Exp.	Exp. Time(sec)	Exp. (R)
	kVp	mA	sec	kVp	mA	sec							
Voiding Cystogram	85	0.1	120	98	100	0.8	3.8	4	90	0.4	264	11.1	0.20
Renal Biopsy	90	2	60	-	-	-	3.8	1	100	4	30	0.5	0.08
Hystero-gram	94	2	30	86	100	2.0	8.9	1	100	0.5	37	1.2	0.03
Hand & Wrist	-	-	-	56	100	2.0	1.3	1	80	0.3	20	1	0.01
Upper GI	90	3	240	100	200	10	104	3	100	4	100	10	1.6

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APPENDIX A

REVIEW OF X-RAY VISUALIZATION TECHNIQUES

In diagnostic x-ray practice the visualization requirements of diagnosis and equipment limitations on sensitivity should govern the radiation exposure. In order to realize the lowest radiation exposure capability of modern diagnostic x-ray equipment certain basic technical propositions should be considered:

1. The viewing system should have sufficient sensitivity for observation of individual x-ray photon interactions in the detector.

2. The number of photons comprising the image should be limited only by the x-ray quantum input, not by loss of light photons along an optical path. All detected x-ray photons should contribute to image information.

3. When the above conditions exist, further reduction in exposure will require an increase in x-ray detection efficiency.

4. The quality and resolution of an x-ray image are interrelated and depend on the number of x-ray photons comprising the image information.

The most common, and least sensitive, detector is the radiographic film-screen combination: a fluorsecent screen viewed by photographic film. The primary detecting medium is the screen. The screen has a relatively low efficiency for converting x-ray photons into light photons to expose the film. Also, a relatively large number of light photons are required to produce one developable grain of silver in the film. Approximately one milliroentgen of x-ray exposure is required to obtain a film density of one, using a high-speed combination (*34*).

Another common detector, yielding higher sensitivity, is the fluoroscope: a fluorescent screen viewed by the eye. The primary detecting medium is also the screen, but sensitivity is increased due to the capability of the eye. Although normal vision is primarily photopic (using the retinal cones) with a threshold of perception higher than the light intensity from the screen, the eye is capable of extremely sensitive scotopic vision at low light levels (using the retinal rods). Tests have indicated a properly dark-adapted eye can respond to as few as 15 to 20 light photons (*31*). Scintillations of the fluorescent screen resulting from individual x-ray photon interactions can be easily discerned. With

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the scintillating low luminance of the fluoroscope and scotopic vision, however, there is a decrease in visual acuity (*30*). As contrast differences become small, a great deal more light is required for the eye to distinguish the difference (*32,34*). The poor resolution of the fluoroscopic screen-eye combination is a major disadvantage.

Photofluorography, utilizing a large fluorescent screen optically coupled to a photographic camera, affords some increase in sensitivity because of image minification. But, there is still the inefficiency of the film, plus losses in the optical coupling system.

A major improvement in detection sensitivity has been achieved with the development of the x-ray image intensifier. The intensifier produces an image similar to that of the fluoroscopic screen, but much brighter. The overall brightness gain results from electron amplification and image minification at the output phosphor. The x-ray image intensifier may be optically coupled to the eye, to film, or to a television camera. When directly viewed, the increased luminance permits photopic vision with increased acuity and resolution. An image limited only by the x-ray quantum input can be readily discerned, but sufficient x-rays must be used to avoid severe statistical fluctuations of the light photons produced. In comparison with other systems, the x-ray image intensifier is capable of higher quantum efficiency and better resolution for a given photon input (*29,32,56,57*).

The x-ray image intensifier optically coupled to film yields acceptable images using considerably less exposure than required for the radiographic film-screen combination. A film density of one may be obtained using 1/10 to 2/10 milliroentgens incident to the input screen of the image intensifier. (See imaging capabilities, section 3.2).

The capability of the x-ray image intensifier optically coupled to a television camera presently offers the most sensitive x-ray image detection system available with adequate resolution. The improvement over direct viewing and film viewing results from the characteristics of television cameras and viewing systems. First, the inherent sensitivity of the television camera tube is greater than that of the eye for equivalent resolution at low light levels; and resolution does not decrease with dark adaptation of the camera. Second, the television system, with video signal amplification, permits observer control of image brightness and contrast over a reasonable range and requires less x-ray input to present a bright, quantum-limited image than direct viewing. Individual x-ray photon-screen interactions can be easily observed using photopic vision. This permits adjustment of the x-ray input to the least possible value necessary for adequate visualization within the limits of intensifier resolution (*35,38*). Other systems do not permit choice of a least possible number of photons to make an x-ray image; x-ray exposure is established more by their lack of sensitivity than by the requirements of visualization.

In choosing the number of photons to produce an x-ray image, the required quality and resolution must be considered. The radiologic image contains two major components: the desired coherent image information exactly representing the spatial distribution of the radiographic densities in the subject under study; and undesirable image noise resulting from statistical fluctuations in photon flux due to the random emission of x-ray photons, random absorption of photons in the subject, and random interaction of photons in the detector.

The quality and resolution of the radiologic image are interrelated and dependent on the amount of coherent information existing in proportion to noise for smaller and smaller picture elements or areas of image subdivision. The information content of the entire image, and any individual picture element, is limited by the number of photons comprising the image, or the element. Any random fluctuation or variance in the number of these photons is considered noise.

The standard deviation of the mean value of the number of photons comprising the coherent information may be used as a measure of image noise or image quality. For example, a radiologic image 10 x 10 centimeters produced by a total of 10^6 photons has an uncertainty in this number of 1000, the square root of 10^6. With a photon flux variation of three times this standard deviation, the mean value of the number of photons making up the image will be within 0.3 percent. Thus, the certainty is great that the total number of photons and the apparent brightness of the complete image will not vary in any discernable degree.

Similarly, the mean value and variance of the number of photons comprising each individual picture element determine resolution capability. Consider a 1 x 1 centimeter element of the 10 x 10 centimeter image, containing 10^4 photons. The standard deviation is 10^2, or 1 percent. With a variation of only 1 percent, the brightness of this square centimeter will appear uniform; even a variation of three standard deviations, or 3 percent, would probably not be noticed. A picture element of 1 x 1 millimeter, however, will contain only 100 photons with a standard deviation of 10, or 10 percent. Three standard deviations would result in a 30 percent variation in brightness among adjacent picture elements. Brightness variations of this degree would noticeably affect resolution of small structures even though the whole image would have a good quality appearance. If the resolving capabilities of the imaging system were extended to 1/10 millimeter picture elements, there would be only 1 photon per element with a brightness variation of more than 100 percent. In the 10 x 10 centimeter image under discussion, resolution would be roughly limited to a 1 millimeter picture element or one line per millimeter. An increase in resolution would require an increase in photon flux and in the total number of photons comprising the image.

For image quality comparisons the relationship between coherent information and noise may also be expressed as a ratio. The concept of signal (coherent information)-to-noise ratio for an image is similar to that for electrical signals in communications. In any given radiologic image, signal-to-noise ratio and quality may be improved by increasing the total number of photons comprising the image, or by reducing the resolution of the imaging system. A reduction in resolution reduces the number of picture elements and increases their size. With the same total number of photons and larger picture elements, there would be an increase in the number of photons per element, and in the signal-to-noise ratio. Thus, choosing the least possible number of x-ray photons to provide the best quality image for visualizing the smallest possible detail also depends upon the resolution selected for the imaging system.

In view of these relationships, the characteristics of the television camera chain to be used with an image intensifier must be carefully considered. Television systems are available with scan rates of 500 to 1000 lines per frame, and offering resolutions of from 400 to about 1000 TV lines. Comparative tests conducted using similar x-ray input rates have shown the 500-line system to be superior for use with present-day image intensifiers (*61*). The tests reflected the deterioration in image quality (signal-to-noise ratio) occurring with improved resolution of the imaging system. Because of this and a desire to use the least possible x-ray photon flux, a 500-line television system was chosen for viewing the image intensifier in the electronic radiography system. Also, the selected system utilizes high efficiency lenses for optical coupling between the image intensifier and the television camera in order to minimize optical photon losses that reduce coherent information content.

Other technical considerations in reducing x-ray exposure include the role of retinal action time in fluoroscopy and the redundancy of real-time fluoroscopic viewing. It is necessary for the eye to view the light output of the fluorescent screen for 1/10 to 2/10 second (*31*). This is true with television viewing as well as direct viewing, with or without x-ray image intensification. An x-ray image is constructed photon by photon until a pattern of light and dark forms a recognizable image. If the photon input rate is too low, only rrandom scintillations can be seen. If the photon input rate is sufficiently increased, the image appears. The perceived image results from the accumulation of all the individual flashes of light produced by the photon-screen interactions during the retinal action time. Real-time fluoroscopy may be considered to be a continuous series of images, each lasting about 2/10 second. If the observed object is stationary, a continuous series of exposures is unnecessary. All the extractable image information is available in any one of the 2/10 second intervals. Longer visibility of the image (and longer x-ray exposure) is required only because one cannot study an image in such a short time. In viewing static objects or structures with little motility, x-ray quanta should be limited to the minimum needed to produce an adequate single image.

These technical considerations led to the development of an "electronic radiography" system which combines the high sensitivity of televised x-ray image intensification with a short duration x-ray exposure similar to that used in radiography.

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APPENDIX B

DETAILS OF THE ELECTRONIC RADIOGRAPHY SYSTEM

The television camera chain selected for the system is a Philips Model XGF7100/01, consisting of an XGF7102 TV camera with type 55850 vidicon or 55876 plumbicon and an XG700 TV camera control unit with XG7103 TV pulse generator. The modular design of the Philips system provides easy access to the circuitry for necessary modifications, and permits use of either plumbicon or vidicon. The camera control unit and pulse generator provide type EIA-RS-170 television sync signals required for the video disk recorder (*63*). Installation of the camera chain and electrical interconnection with existing laboratory x-ray equipment was simple and inexpensive.

The camera and camera control unit were modified to permit external beam blanking and selection of automatic or manual video gain control. Control of beam blanking is accomplished by a compact high-speed mercury relay (RYA) installed in the camera as shown in figure 21. When the relay is energized, it biases the vidicon cathode to a level of about 100 volts positive, cutting off the electron beam; otherwise, the vidicon operates normally. Conventional real-time fluoroscopy with TV viewing requires automatic control of video gain. For electronic radiography, a pre-settable manual gain control is more satisfactory. A relay (RYB) added to the camera control unit, figure 21, enables the operator to select automatic or manual control. These modifications do not interfere with normal camera chain operation for real-time fluoroscopy. When the x-ray generator is energized for real-time fluoroscopy, the scanning beam and automatic gain control remain on. When the system is energized for electronic radiography, the camera chain is automatically switched to manual gain control and beam blanking takes place in the proper time sequence as shown in figure 4, section 2.

The magnetic disk recorder used in the system is an MVR Corporation Videodisc Recorder, Model VDR 200MM with electronic logic to provide an image "freeze" and "update" feature. This is necessary in order to provide single-frame TV image recording with instant playback, and instant erasure for recording and replay of a new image. At the time of selection, the MVR unit was the only readily available commercial recorder with this feature.

A block diagram of the electronic radiography system is shown in figure 22. The composite video signal from the camera chain is processed by recorder circuits to provide TV sync for regulation of disk rotational speed and operational control signals synchronized with the vertical sync pulses. When an electronic radiograph is

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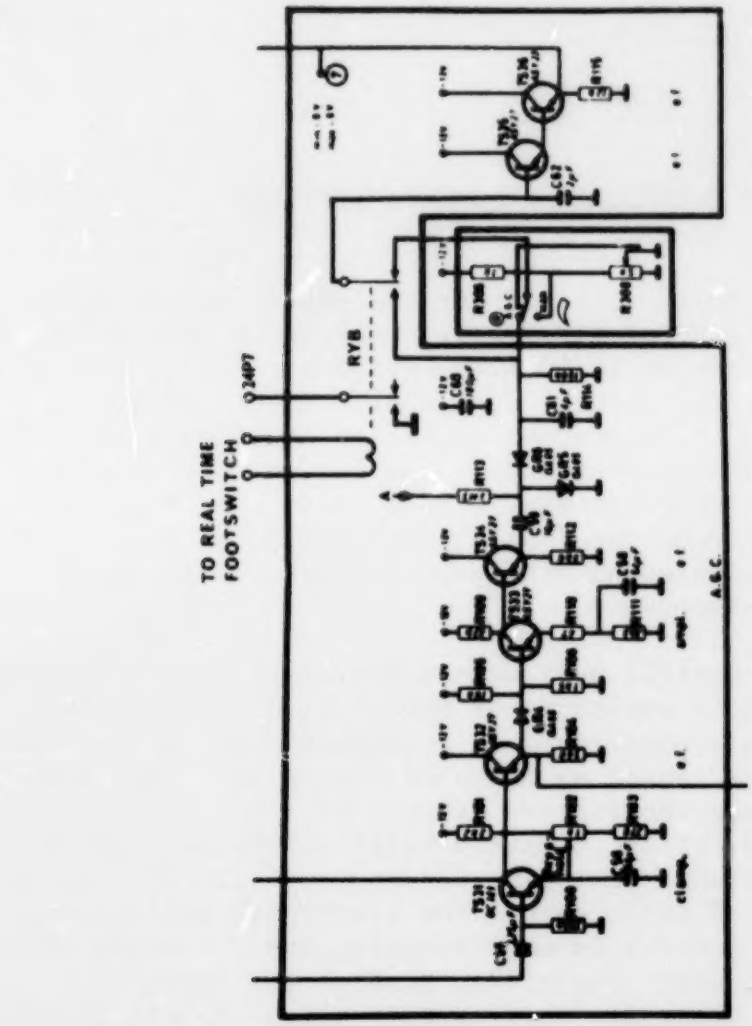

Figure 21. Schematic diagram of Philips camera chain, as modified.

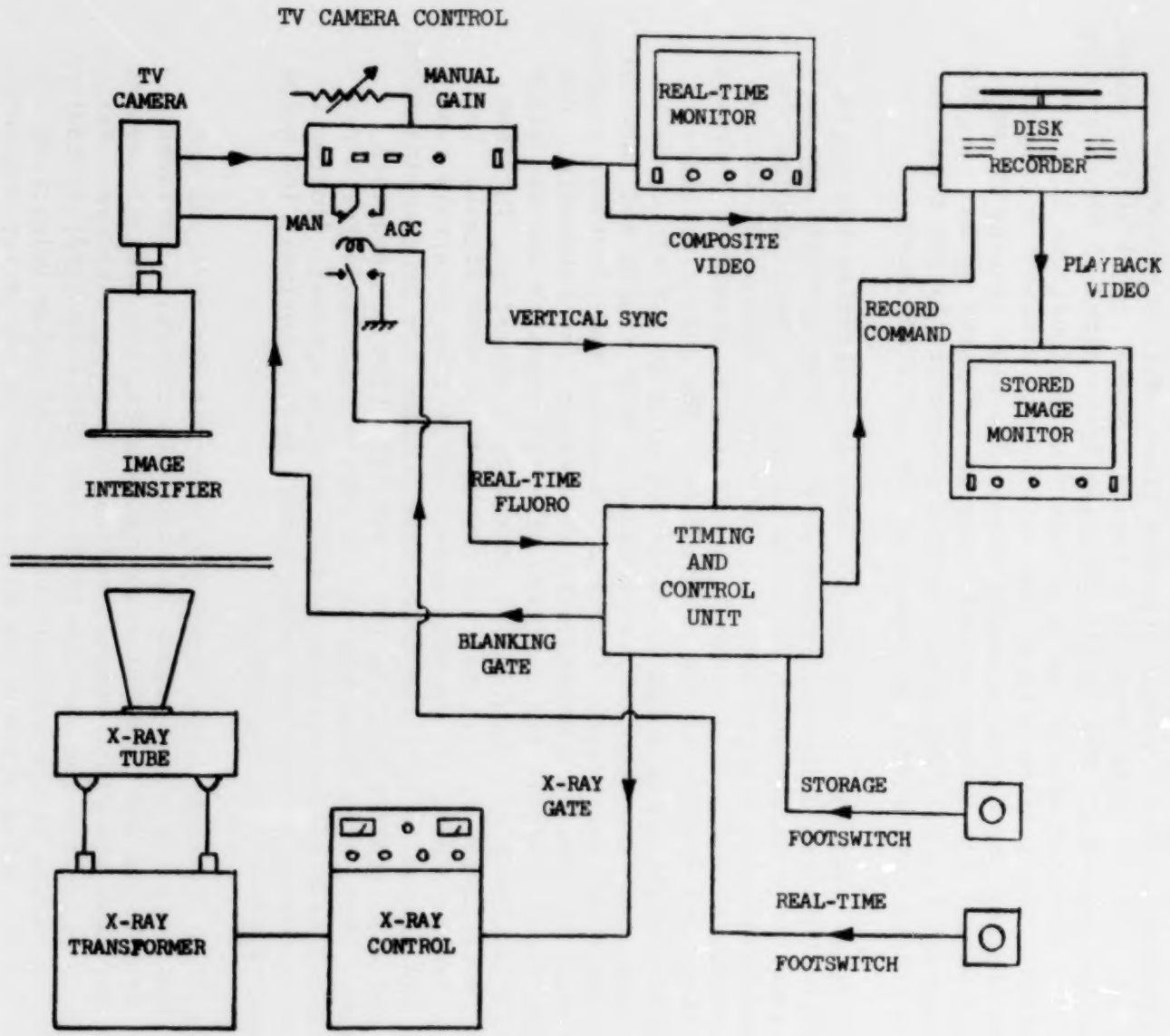

Figure 22. Block diagram of electronic radiography system.

desired, the Storage Footswitch is depressed and a command signal from the exposure and timing logic in the Timing and Control Unit indicates that the scanning beam should be blanked. The vertical sync pulse immediately after the command signal triggers the beam OFF, and the x-ray generator ON for a preset exposure time. When the exposure terminates, control logic provides a record command signal at the proper time for the recorder. The record function is actuated at the beginning of the next vertical sync pulse by a record-gate signal two TV fields in duration. The leading edge of the record-gate produces a trigger pulse to unblank the camera scanning beam. The beam remains ON until a command signal for another stored image is initiated by the footswitch. The Timing and Control Unit also provides automatically the repetitive exposure timing for sequential images at pre-selected rates.

Schematic diagrams of the circuit modules comprising the Timing and Control Unit are shown in figures 23-26. These circuits are a second-generation design which replaces an earlier, more complex, and sometimes unreliable control method. The revised Timing and Control Unit provides more flexible control, better timing accuracy, increased reliability, and simplified synchronization. The design utilizes integrated circuit logic constructed on two plug-in circuit cards (Timer Logic and Timer Control) as well as a Power Supply and Selector Panel. The Timer Logic card, figure 24, contains two identical programmable timers to provide independently adjustable time intervals. One timer (IC 1-12) controls the duration of x-ray exposure and the other (IC 13-23) controls the duration of camera beam blanking. The time base for both timers is derived from the vertical sync signal. The Selector Panel, figure 23, permits selection of time intervals from 1/60 to 1/4 second (1 to 15 vertical sync pulses) for programming either timer, and also enables setting the repetitive time for sequence exposures. Thus, time intervals may be chosen separately for x-ray exposure and beam blanking; this feature permits optimal adjustment of target-integration time and x-ray quanta for an optimal, low-noise, low-exposure electronic radiograph.

The Timer Control card, figure 25, converts the vertical sync signal into suitable clock pulses to drive the timers, interfaces the storage footswitch and repetition rate generator, and provides output signals for beam blanking, record command, and x-ray exposure. Relays are used to interface the storage (RY1) and real-time (RY2) footswitch circuits to reduce the possibility of electrical noise triggering the circuit logic. Solid state drive is provided for the x-ray contactor and beam blanking relay. The image "freeze" logic is triggered directly so that recording will be instantaneous.

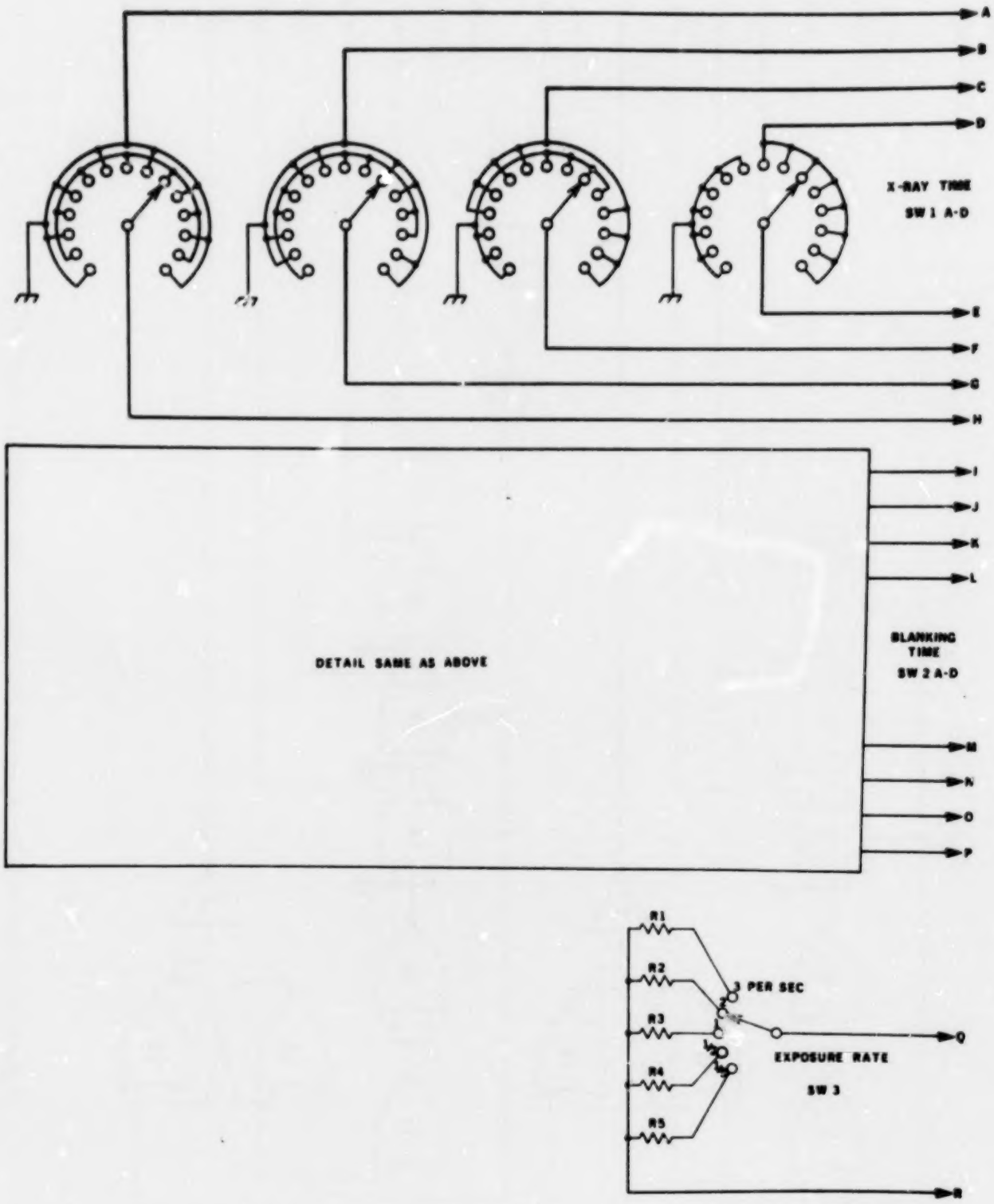

Figure 23. Schematic diagram of Timing and Control Unit SELECTOR PANEL.

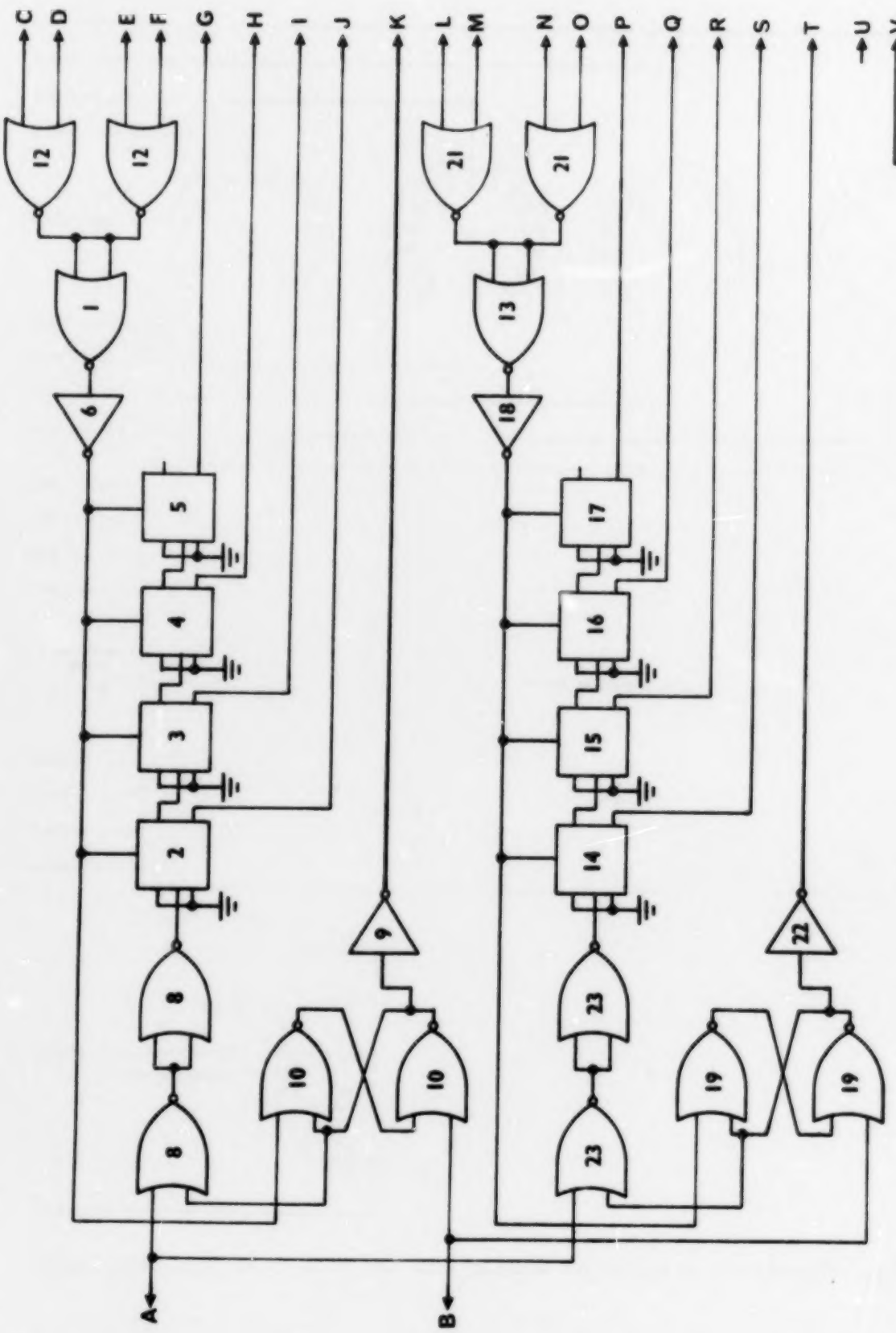

Figure 24. Schematic diagram of Timing and Control Unit TIMER LOGIC.

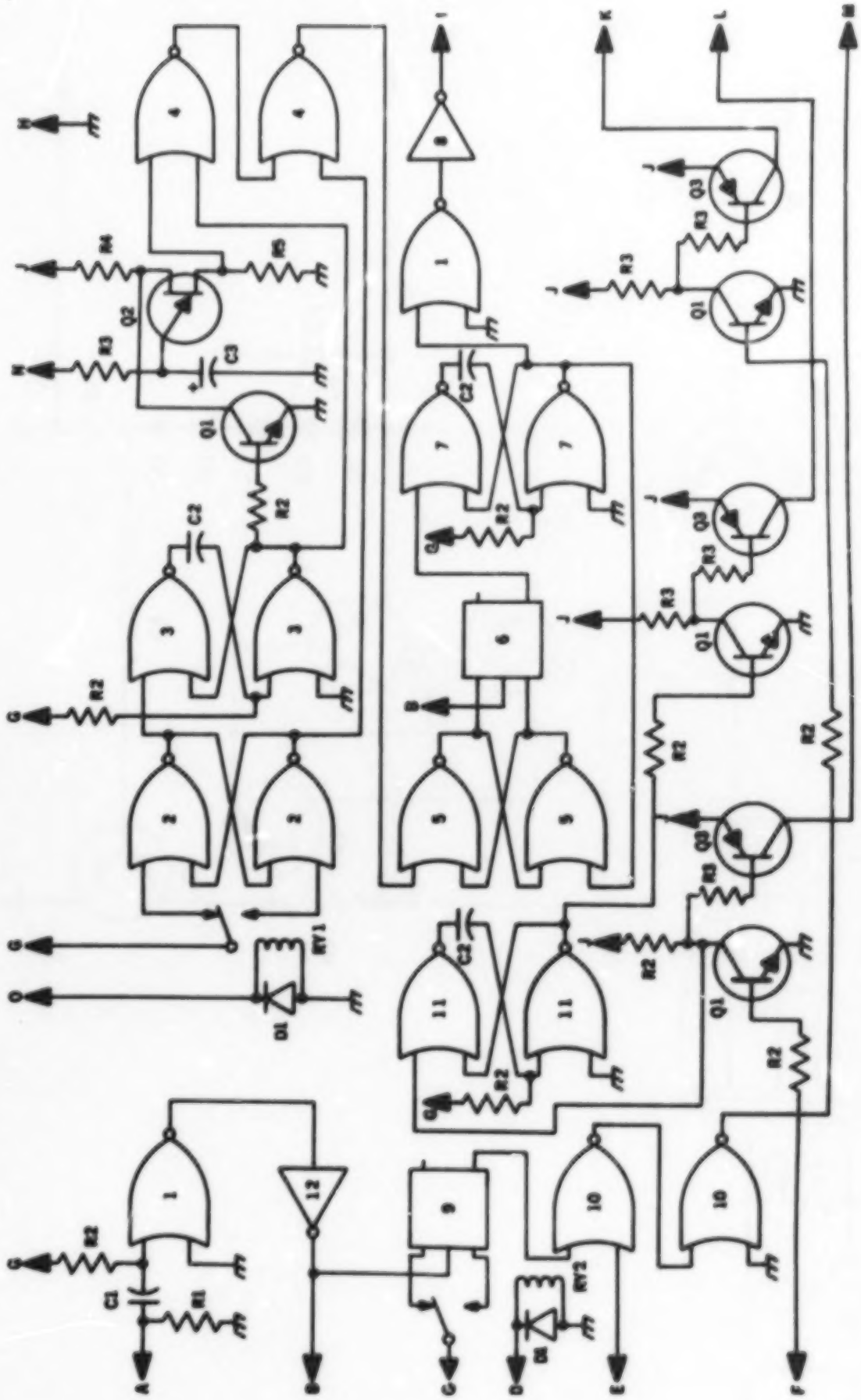

Figure 25. Schematic diagram of Timing and Control Unit TIMER CONTROL.

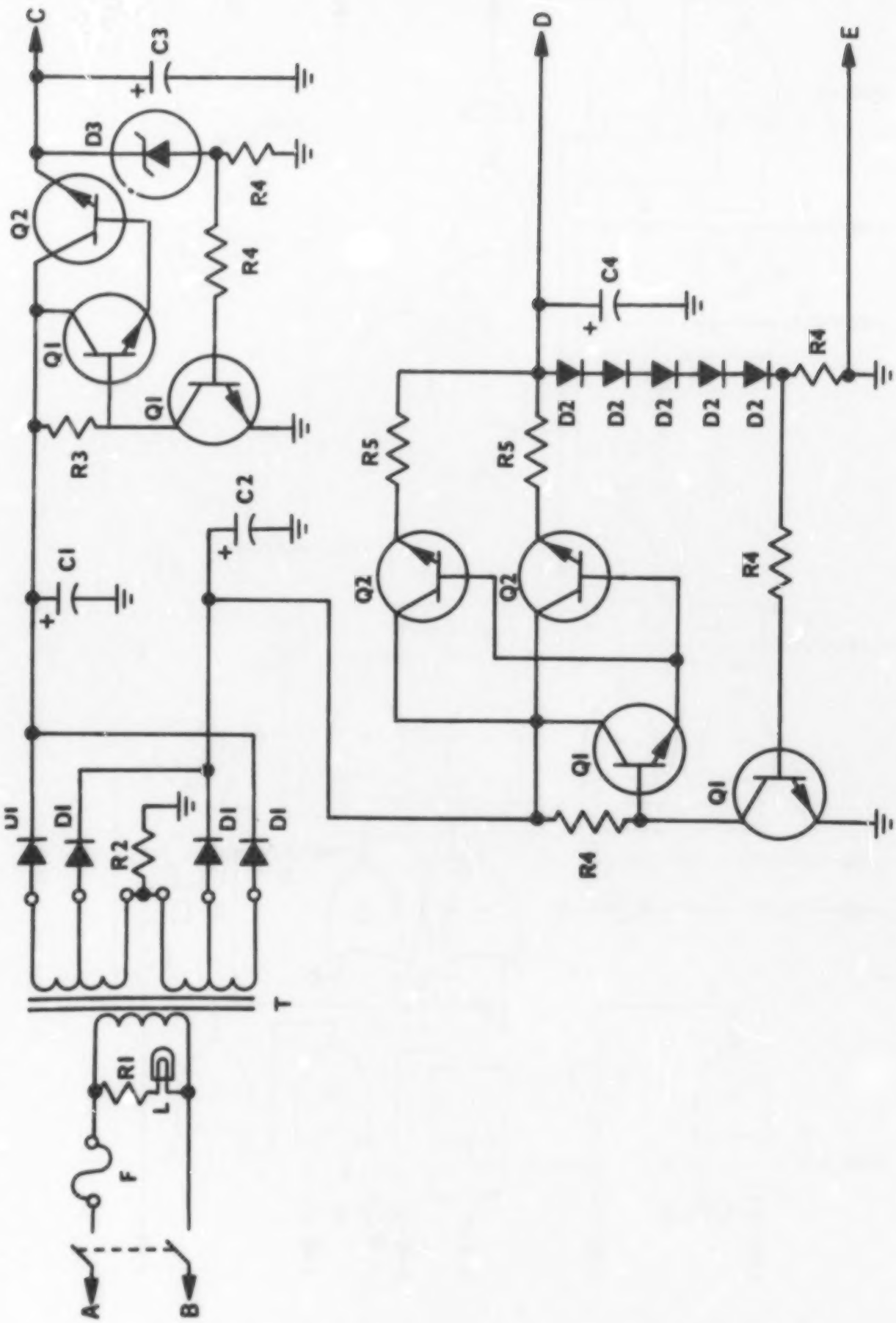

Figure 26. Schematic diagram of Timing and Control Unit POWER SUPPLY.

The Timing and Control Unit Power Supply, figure 26, is a conventional regulated supply. The connection codes and parts lists for all Timing and Control Unit circuits are given in figures 27 and 28. The integrated circuits used in the Timer Logic and Timer Control circuits are Fairchild RTL micrologic units. Operation of these two circuits is described below.

Timer Logic is initiated by a positive "start" pulse generated in the Timer Control on operation of RY1 by the storage footswitch. This pulse is applied to the input of flip-flop IC-10, figure 24, causing its output to be at logic 0 (0-0.25V). The output of IC-10 is coupled to the inputs of IC-8 and IC-9. IC-8 is a gate which allows clock pulses from the Timer Control to pass to the exposure timer when its input is at logic 0, and prevents passage when at logic 1 (1.5-3.5V). IC-8 also inverts the clock pulses for proper signal polarity to the input (IC 2-5) of the x-ray timer section of the Timer Logic. When the binary counter reaches the time state selected on the Selector Panel, figure 23, all inputs to IC-12 are at logic 0 and the output is at logic 1. This output, amplified by IC-1 and IC-6, is applied to reset the binary counter and flip-flop IC-10. Reset of IC-10 places a logic 1 signal on the input of IC-8 to stop the clock pulses. The output of IC-10 is also inverted and amplified by IC-9 to obtain a gate signal for the x-ray contactor-driver (IC-10) of the Timer Control, figure 25. This gate is logic 1 for x-ray ON, and logic 0 for x-ray OFF.

Operation of the beam blanking timer section (IC 13-23) of the Timer Logic is identical to the x-ray timer section. The output of IC-19 is inverted and amplified by IC-22 to provide the unblanking and record gate signal. This gate is applied to the camera blanking-driver and record-trigger generator (IC-11) of the Timer Control, figure 25. This gate is logic 1 for beam OFF and logic 0 for beam ON and initiates the trigger pulse for the recorder "freeze" logic.

The TV vertical sync signal for input to the clock pulse generator should be minus 4 volts peak-to-peak. The outputs are positive 12-volt signals for the x-ray contactor, beam blanking relay, and recorder logic.

The two television monitors selected for use with the system are transistorized Conrac Model RLB14 with a high definition 14-inch picture tube.

SELECTOR PANEL, FIGURE 23

A. X-ray Time Binary Output 1
B. " " " " 2
C. " " " " 4
D. " " " " 8
E. X-ray Time Gate Input 1
F. " " " " 2
G. " " " " 4
H. " " " " 8
I. Blanking Time Output 1
J. " " " 2
K. " " " 4
L. " " " 8
M. Blanking Time Gate Input 1
N. " " " " 2
O. " " " " 4
P. " " " " 8
Q. Exposure Rate Time Constant
R. +12 V

TIMER LOGIC, FIGURE 24

A. Clock
B. Start
C. X-ray Time SW Input 8
D. " " " " 4
E. " " " " 2
F. " " " " 1
G. X-ray Time SW Output 8
H. " " " " 4
I. " " " " 2
J. " " " " 1
K. X-ray Gate
L. Blanking Time SW Input 8
M. " " " " 4
N. " " " " 2
O. " " " " 1
P. Blanking Time SW Output 8
Q. " " " " 4
R. " " " " 2
S. " " " " 1
T. Blanking Gate
U. +3.6 V
V. Gnd

TIMER CONTROL, FIGURE 25

A. Vertical Sync Input
B. Clock Out (to Timer Logic)
D. Real-Time Footswitch
E. X-ray Gate Input
F. Blanking Gate Input
G. +3.6 V
H. Gnd
I. Start Output (to Timer Logic)
J. +12 V
K. X-ray Contactor Drive
L. Record Trigger
M. Camera Blanking
N. Rate Switch
O. Storage Footswitch

POWER SUPPLY, FIGURE 26

A. 115 V AC
B. 115 V AC
C. +12 V
D. +3.6 V
E. Gnd

Figure 27. Connections for the Timing and Control Unit

SELECTOR PANEL, FIGURE 23

R1 = 22,000 ohms
R2 = 33,000 ohms
R3 = 47,000 ohms
R4 = 100,000 ohms
R5 = 330,000 ohms

TIMER LOGIC, FIGURE 24

IC 6, 9, 18, 22 = Fairchild micrologic 900, or equivalent
IC 1, 8, 10, 12, 13, 19, 21, 23 = Fairchild micrologic 914, or equivalent
IC 2-5, 14-17 = Fairchild micrologic 923, or equivalent

TIMER CONTROL, FIGURE 25

IC 8, 12 = Fairchild micrologic 900, or equivalent
IC 1-5, 7, 10, 11 = Fairchild micrologic 914, or equivalent
IC 6, 9 = Fairchild micrologic 923, or equivalent

R1 = 75 ohms, 1/2 W
R2 = 3,300 ohms
R3 = 10,000 ohms
R4,R5 = 1,000 ohms

RY1,RY2 = SPDT 12 V Relay with Hg wetted contacts and 1N645 across coil

C1 = 0.22 mfd, 100 V
C2 = 0.005 mfd, 50 V
C3 = 10 mfd, 15 V

Q1 = 2N3903
Q2 = 2N2646
Q3 = 2N3905

POWER SUPPLY, FIGURE 26

C1 = 1,000 mfd, 50 V
C2 = 8,200 mfd, 25 V
C3 = 20 mfd, 25 V
C4 = 50 mfd, 15 V

D1 = 1N4001
D2 = 1N2069
D3 = 1N963B

T = 117 V pri. to 18-9-0-9-18 V sec. Signal Transformer Co. No. 36-1

R1 = 100,000 ohms, 1/2 W
R2 = 3 ohms, 5 W
R3 = 10,000 ohms, 1/2 W
R4 = 1,000 ohms, 1/2 W
R5 = 0.18 ohm, 1 W

Q1 = 2N3903
Q2 = 40347V1

L = Neon Lamp, 1/25 W

F = 1 A Slo-Blo

All resistors 1/4 W, unless otherwise indicated.

Figure 28. Parts list for the Timing and Control Unit

TECHNICAL REPORTS

(continued from inside of front cover)

MORP 68-9	Development and Evaluation of an Automatic Collimator for Medical Diagnostic X-ray Machines (PB 180 528 $6.00)
MORP 68-10	Survey of the Use of Radionuclides in Medicine: Preliminary Report (Superseded by BRH/DMRE 70-1)
MORP 68-11	Dental Surpak Summary Report (PB 184 356 $3.00)
MORP 68-12	Particle Accelerator Safety Manual (Supt. of Doc., GPO-$1.25) (PB 178 325 - microfiche only)
MORP 68-13	PHS Film Badge Program (In preparation)
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BRH/DMRE 72-2	National Conference on College Affiliated Educational Programs in Radiologic Technology (Supt. of Doc., GPO-$2.25, stock no. 1715-0026) (PB 202 867 - microfiche only)